LOAD FLOW CONTINGENCY EVALUATION AND OPTIMAL POWER DISPATCH IN LARGE SCALE POWER SYSTEMS-DEVELOPMENT OF NEW AND MORE EFFICIENT METHODS

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

By

N. ARUMUGAM

to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

AUGUST, 1980

DEDICATED TO

MY BELOVED

PARENTS

CERTIFICATE

Certified that this work entitled "Load flow, contingency evaluation and optimal power dispatch in large scale power systems - Development of new and more efficient methods" by N. Arumugam has been carried out under our supervision and this work has not been submitted elsewhere for a degree.

Dr. R.P. Aggarwal
Professor

Dr. M.A. Pai*
Professor

Department of Electrical Engineering
Indian Institute of Technology
Kanpur.

*Presently on leave to U.S.A. as Visiting Professor, Department of Electrical Engineering, Iowa State University, Ames, Iowa.

ACKNOWLEDGEMENTS

I am deeply indebted to my thesis supervisors Dr. M.A. Pai and Dr. R.P. Aggarwal, who suggested the problem and gave incessant guidance and encouragement.

I am highly thankful to Dr. K.R. Padiyar and Dr. L.P. Singh for some useful discussions in connection with this work. Special thanks are due to all my fellow-research scholars in the Power Group and other friends for their cooperation.

My sincere thanks are due to the authorities of Annamalai University, Annamalai Nagar, Tamil Nadu for granting three years study leave to do the research.

I am happy to acknowledge the facilities for research and financial support provided by the authorities of I.I.T. Kanpur.

I take this opportunity to appreciate my wife Savithri and children Geetha, Kumar and Ram for their forbearance throughout this work.

Lastly I thank Mr. C.M. Abraham for his patient and skilful typing.

N. Arumugam

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PRINCIPAL SYMBOLS

n	=	number of buses in the system
N	=	total number of areas in a multiarea system

Let the subscripts

'G' represents the voltage controlled buses including the slack bus

'L' represents the load buses where P and Q are specified

'v' represents the voltage controlled buses only

n_v	=	number of voltage controlled buses in the system
n_L	=	number of load buses in the system
n_G	=	number of voltage controlled buses including the slack bus in the system
n_p	=	number of generators in the system
n_s	=	number of buses in the system excluding the slack bus
θ_i, V_i	=	voltage angle, magnitude at bus i
θ_{ij}	=	$\theta_i - \theta_j$
e_i, f_i	=	real and imaginary components of the voltage
E_i	=	$V_i \angle\theta_i = e_i + j\, f_i$ = complex bus voltage at the ith bus
Y_{ij}	=	$G_{ij} + j\, B_{ij}$ = 'ij'th element of bus admittance matrix $[Y] = [G] + j[B]$
y_{ij}	=	$\hat{g}_{ij} + j\, b_{ij}$ = admittance of line i,j
t_{ij}	=	tap ratio of the transformer connected to the branch i,j

$P_{Gi} + j\, Q_{Gi}$	=	real and reactive power generations at bus i
$P_{Li} + j\, Q_{Li}$	=	real and reactive power loads at bus i
$P_i + j\, Q_i$	=	net real and reactive power injections at bus i
$[x]$	=	state (dependent) vector
$[u]$	=	control (independent) vector
$[p]$	=	parameter vector
$[I]$	=	bus current vector
$[\lambda]$	=	Lagrange multiplier vector
$[\hat{I}]$	=	identity matrix
α	=	acceleration factor
β	=	step length
γ	=	penalty factor
ε_t	=	convergence tolerance
L	=	Lagrangian function
a_{oi}, b_{oi}, c_{oi}	=	cost coefficients of generator i
$[g(x,u,p)]$	=	general power flow vector
$[g_c(x,u)]$	=	cut line power flow vector
$[h(x,u)]$	=	functional inequality constraints vector
$F(x,u)$	=	objective function
$\|\|A\|\|$	=	$\max\limits_i \{ \sum\limits_j \|a_{ij}\| \}$

T denotes Transposition

* denotes conjugation

The other symbols in the text are defined as and when they are introduced.

SYNOPSIS

N. ARUMUGAM

Ph.D.

Department of Electrical Engineering
Indian Institute of Technology, Kanpur

July, 1980

LOAD FLOW CONTINGENCY EVALUATION AND OPTIMAL POWER DISPATCH IN LARGE SCALE POWER SYSTEMS-DEVELOPMENT OF NEW AND MORE EFFICIENT METHODS

This thesis concerns itself with the development of new and more efficient solution methods for load flow, contingency evaluation and optimal power dispatch in large scale power systems. Load flow is essential for power system planning, operation and control and provides voltages and power flows at different points in power system network for different operating conditions. Contingency evaluation involves determining the security of a system with reference to a set of next contingencies and constitutes the main function of the power system security analysis. Security functions like security monitoring and security analysis are now incorporated into the computer program to deal with different operating conditions as well as disturbances. On-line monitoring and real-time control of the system using process computer is essential in order to prevent or minimize costly system

breakdowns. This led to the development of powerful calculation procedures for load flow and contingency evaluation. These techniques must be simple, efficient and fast for implementation in real-time on moderate size process control computers. The Newton-Raphson method (NM) is the basic practical method best suited for off-line studies because of its quadratic convergence rate and better accuracy. Numerous other methods of load flow and contingency evaluation have been tested and published for off-line and/or on-line studies. The fast decoupled technique of Stott in polar coordinates (FDLP) gained popularity over other methods due to its fast computing speed and moderate memory requirements for off and on-line calculations. Recently, second order load flow techniques have been presented to improve accuracy and to reduce computer time of NM.

The problem of optimal load flow (OLF) is very important because of the high fuel and other operating costs. The solution of OLF gives the values of control variables such as real and reactive power generations and transformer tap ratios for which the system operating cost is minimum. The OLF calculation is a complex nonlinear programming problem due to the large number of variables and constraints. To solve OLF efficiently for large practical systems, fast and accurate methods of load flow solution are needed. A comprehensive comparative analysis of different optimization techniques for

the solution of OLF was given by Happ and Sasson. Dommel and Tinney proposed a practical and efficient method for the calculation of OLF by using NM. Later on, application of FDLF in the place of NM is also reported.

The function of the economic dispatch program is to allocate the real power generation among the available on-line generating units so that the operating cost is minimized. To implement on real-time basis, it requires advances in the accurate calculation of penalty factors or a power flow solution which is both fast and accurate. This problem has been solved with approximate loss formulas as well as more accurate and faster methods.

However, there is still a scope of improving these well known methods of load flow, contingency evaluation, optimal load flow and economic dispatch in terms of computation time.

Present day power systems are large because of greater interconnections. To analyse such large scale systems with limited core storage, application of sparsity oriented ordered elimination techniques and/or the various piecewise, decomposition and diakoptic techniques is needed. Recently, the hierarchical control of power system has been and continues to be studied intensively. In this method, the original system is decomposed into several smaller subsystems or areas coordinated by a central agency. It requires the use

of small multi-computers with significant reduction in computer storage requirements. Sometimes, a net saving in computation time is also achieved. A survey of literature reveals that the hierarchical solution methods for OLF are limited to the optimization of real power flow only. (Control of reactive power flow and transformer tap ratios is neglected).

Keeping the above in view, this thesis presents solution techniques to the different problems considered. The scope of thesis is broadly divided into two parts.

i) Development of new load flow solution methods along with a theoretical study of the convergence characteristics for off-line and/or on-line studies and its adaptation to contingency evaluation and optimal load flow.

ii) Development of load flow and optimal load flow methods for large scale power systems by a two level computation based on hierarchical control theory.

The chapterwise summary of the work covered in this thesis is given as follows :

Chapter I introduces the problems of load flow, contingency evaluation and optimal load dispatch. Then, the theory of hierarchical control is presented. A brief review of the state of the art and the scope of the thesis are enumerated at the end.

Chapter II is devoted to the development of the following new load flow solution methods. i) Fast decoupled load flow in rectangular coordinates (FDLR): The rectangular version is derived by linear transformation from FDLP as well as direct from NM. It offers computational advantages of 5 to 10 percent speed over the polar version, while the memory requirements are similar. ii) Newton-Richardson method (NRM) : This method is a variant of NM, obtained by combining both the chord method and the Newton-iterative method. It is about 2 times faster than NM for large systems and has the same solution accuracy and convergence rate as NM. The Jacobian is readily available for important applications like optimal power dispatch, sensitivity analysis and security constrained optimization, iii) Network-reduction method (NETR): The method is based on eliminating P-Q buses using sparse matrix techniques and applying NRM to an equivalent system consisting of only P-V buses. It is comparable to FDLP with regard to computing speed and memory space for the medium size systems. Test results of the IEEE 14 bus, 30 bus, and 57 bus test systems and a heavily loaded 23 bus system using FDLR, NRM and NETR algorithms are presented and compared with the results of NM and FDLP. In addition, the results obtained using FDLR for a 133 bus system are compared with the result of FDLP.

Chapter III is concerned with contingency evaluation needed for power system security assessment. FDLR and NETR load flow algorithms developed in Chapter II are extended for the rapid and efficient simulation of network and/or power outages. FDLR incorporates the matrix inversion lemma and NETR adapts both the matrix inversion lemma and matrix updating algorithm in order to make use of the base case factors to obtain all contingency states as in prevalent competing methods due to Stott and Peterson. The proposed FDLR algorithm is faster than FDLP by about 10 percent. But the NETR algorithm has computational advantages over FDLP if the number of P-V buses is roughly about 10 percent of the total number of buses in the system. Digital simulation of a number of outage cases is carried out on the IEEE 14 bus, 30 bus and 57 bus test systems. The significant results of these system studies are presented and compared with the result of FDLP.

Chapter IV deals with optimal load flow solutions and economic load dispatch. A new optimal load flow calculation method using NRM load flow algorithm and a new fast economic load dispatch solution using NETR load flow algorithm in the solution approach of Dommel and Tinney are proposed. The method of solution using NRM gives an overall advantage in speed of approximately 2 to 2½ times compared to the approach of Dommel and Tinney without affecting the solution accuracy,

convergence properties and generality of formulation. The solution approach by NETR is based on the assumption that the voltage magnitude variations at the P-Q buses are not too sensitive to the real-power changes and the reactive power equations depend weakly on the phase angles of the voltages. This makes the algorithm very fast and operate with less storage. The optimal load flow and economic dispatch results of the adapted IEEE 14 bus, 30 bus and 57 bus test systems using the proposed NRM and NETR algorithms respectively are presented and compared with the result of Dommel and Tinney's approach.

Chapter V describes a two level computational procedure for load flow and optimal load flow calculations in large scale power systems based on hierarchical control theory. It can be regarded as an application of decomposition. It is suitable for multicomputer configuration with less core storage requirement. It combines both the advantages of sparsity and decomposition. A two level load flow calculation method is described using NM, NRM and FDLP. Then, the multi-area optimization problem is formulated as an additively separable nonlinear programming problem in such a way that the optimization of both real and reactive power and transformer tap ratios is possible. The total Lagrangian function is decomposed into several sub-Lagrangians by introducing pseudo variables. The second level determines the pseudo

variables and the associated Lagrangian multipliers. The first level determines the subsystems solutions and the associated Lagrangian multipliers. The solution algorithm for optimal load flow calculations considering both equality and inequality constraints using the overall cost as the objective function is given in detail. The practical applicability of the proposed two level technique is demonstrated by obtaining the load flow and optimal load flow results for the adapted IEEE 30 bus and 57 bus test systems which are torn into 2 or 3 subsystems or areas.

Chapter VI gives a theoretical study of the convergence characteristics of the load flow solution methods (FDLR, NRM and NETR) developed in Chapter II. The different load flow algorithms are expressed into the general nonlinear iterative scheme. For these algorithms, the convergence conditions, which guarantee the existence and uniqueness of load flow solution in a specified region of interest, are obtained by an application of the convergence theorem used by Wu. These conditions are verified by using an adapted IEEE 14 bus test system for different R/X ratio of the heavily loaded line.

Chapter VII reviews the major contributions in the thesis. Further possibilities of research in this area are also indicated.

CHAPTER I

INTRODUCTION

1.1 LOAD FLOW STUDIES

The solution of the load flow problem is carried out extensively on a digital computer for power system planning, operation and control. This is essential both for off-line and on-line applications. The objective of this study is to determine the phase angle and reactive power on each P-V bus and the phase angle and voltage magnitude on each P-Q bus subject to the constraints on the real and reactive power at the P-Q buses and the real power and voltage magnitude at the P-V buses. The digital solution of load flows has been studied extensively using different forms [3,5,8,14,20,90] of nonlinear equations. The formulation in the nodal admittance reference frame is preferred, since it preserves sparsity of the network. An excellent review by Stott [25] gives the salient features and the comparative merits of different load flow solution methods. The important properties required of a load flow solution method are high computational speed, low storage, reliable convergence and versatality. Further, it must be suitable for modern applications like security analysis, optimal load flow and economic dispatch calculations.

1.2 POWER SYSTEM SECURITY

Recently, a new strategy of security control has emerged for the reliable operation of electric power systems and to prevent black-outs and blown-outs. This has made a significant impact on power industries and the security functions are being implemented with the aid of on-line computers in more than 100 power system control centres [41] throughout the world.

1.2.1 Security Concept

DyLiacco [26] identified three modes for power system operation namely the normal state, the emergency state and the restorative state. A power system is subjected to two sets of constraints. i) load constraints (load flow equations) ii) operating constraints (maximum or minimum limits on system variables such as voltages, real and reactive power generations, transformer tap ratios, phase angle differences etc.). By definition, normal state is one in which both the load and operating constraints are satisfied. A system is in emergency state when the operating constraints are not completely met. A system is in restorative state, if the operating constraints are satisfied but not the load constraints. The normal state may be either secure or insecure. A normal state is said to be secure, if it undergoes any contingency without getting into an emergency condition. If there is a possible contingency which causes the system to

enter the emergency state, then the normal system is insecure. Fig. (1.1) gives a typical scheme for computer software organization [41] that links the various security oriented functions together. The objective of security functions is to keep the system operating in normal state.

1.2.2 Security Analysis

Security analysis comprises of two functions :

(1) Contingency evaluation: It determines the security of the system with reference to a set of next contingencies, i.e. verifies whether the normal system is secure or insecure.

(2) Preventive control : It determines suitable preventive action, when the system is insecure.

1.3 OPTIMAL LOAD FLOW STUDIES

The optimal load flow study determines an operating state or load flow solution in which a certain objective function like fuel cost or system loss is minimized taking the generator real powers, voltage magnitudes and transformer tap ratios as control variables subject to the operating constraints of the power system. A number of problem formulations [39,70,73] exist using different choices of objective functions and constraints. In its more general form, the problem is a complex non-linear and constrained mathematical programming problem. A variety of simplifications by linear or quadratic programming have been reported

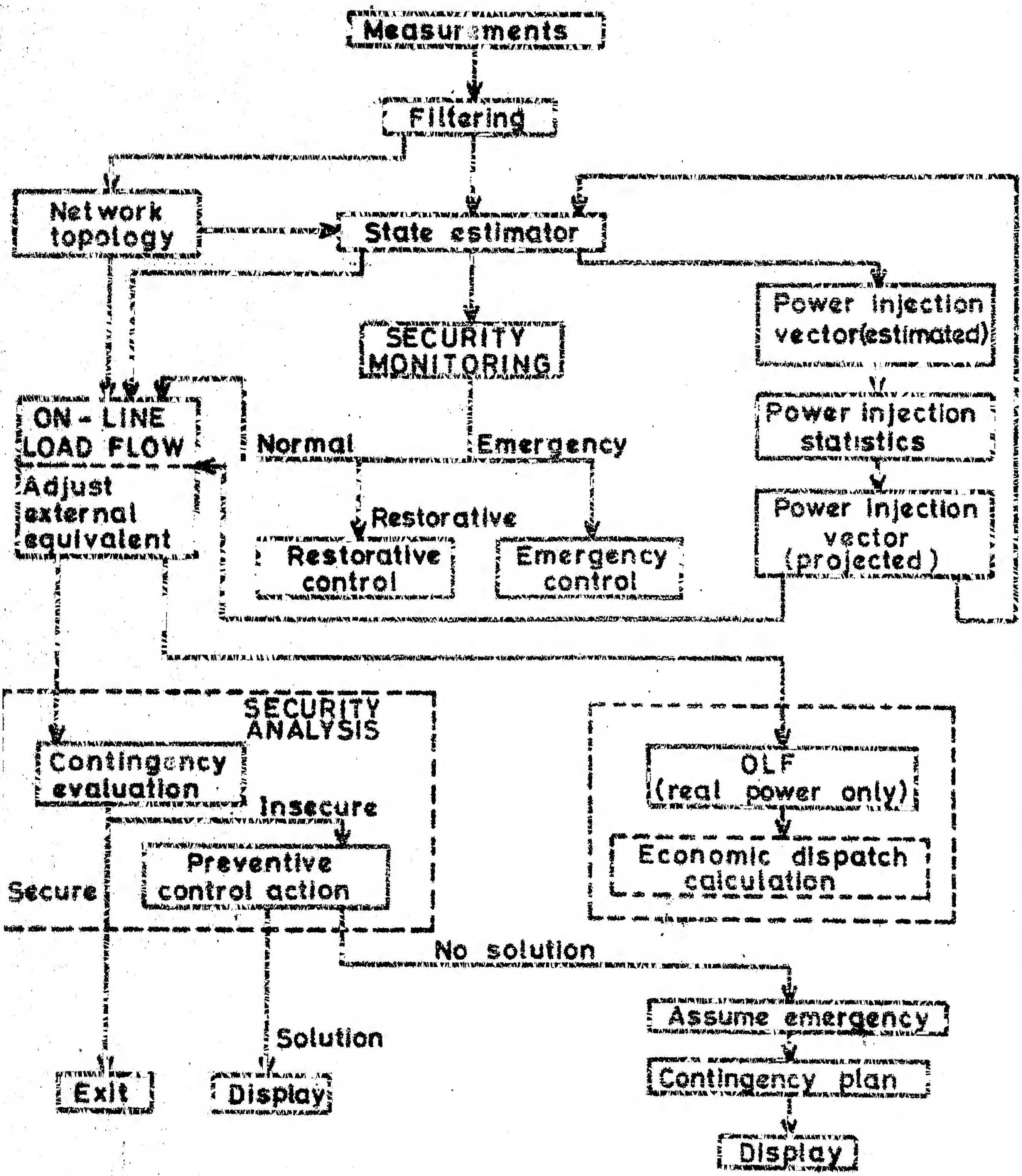


FIG.1.1 COMPUTER ORGANIZATION WITH SECURITY ORIENTED FUNCTIONS.

in detail [73,78,106,109]. Classical economic dispatch can be considered as a particular case of optimal load flow with only generator real powers as control variables and no security constraints. Many power system control centres today still operate with the above concept, the calculations being made on-line every few minutes.

1.4 HIERARCHICAL CONTROL THEORY

Hierarchical control methods are becoming popular for large scale power system problems. There are two kinds of hierarchy which are of great importance.

(1) Multilayer Hierarchy : This concerns the decomposition of the function of system organization into layers. Each layer supervises the system with a different model. This kind of hierarchy is used in off-line as well as real-time applications using on-line centralized computer.

(2) Multiechelon or Multilevel Hierarchy : In this, the large system is decomposed into many subsystems on the basis of the physical structure of the system. The overall solution is obtained by proper coordination. In general, different methodologies presented by Mesarovic [89] and Haimes [104] are highly beneficial in the coordination of the subsystems of a given decomposition. This kind of hierarchy is useful when a decentralized multicomputer configuration (Fig. 1.2) is employed with the help of regional or area computers,

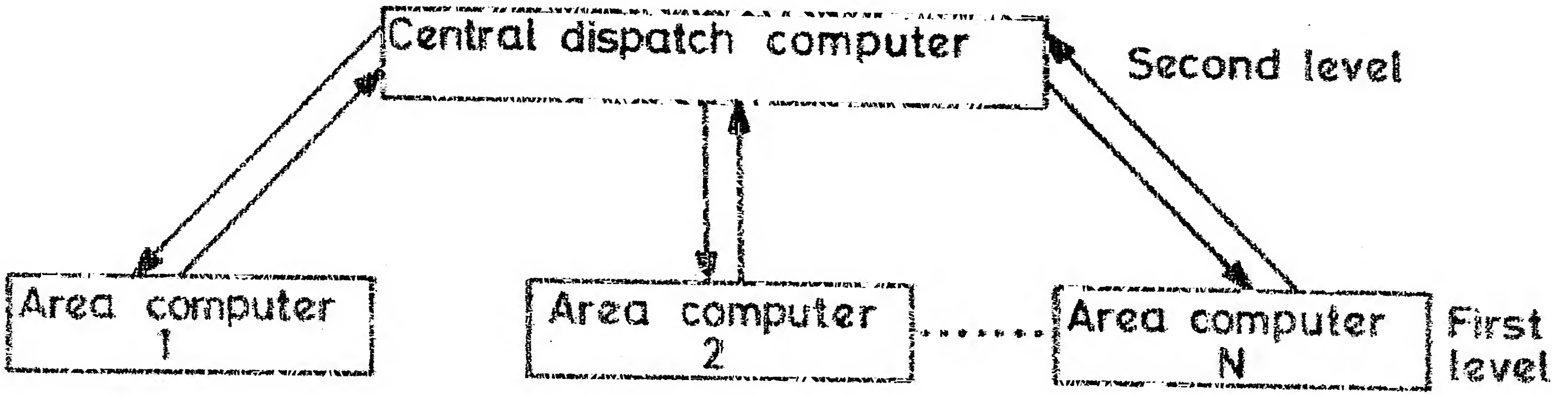


FIG.1.2 MULTIAREA TWO LEVEL COMPUTER STRUCTURE.

coordinated by a central dispatch computer. The decentralized hierarchical structure has been considered by several authors for state estimation [99,107], reactive power and voltage control [98,105], economic dispatch calculation [87,96,108] and transient stability [100].

This thesis addresses itself to the important problems of power system just discussed namely, load flow, contingency evaluation, optimal load flow and economic dispatch. It begins with the development of new load flow solution methods which are competitive and superior in some respects to the existing methods. Then, these methods are adapted to contingency evaluation and optimal power dispatch. Before delineating the theoretical study of the convergence characteristics of the new load flow solution methods at the end, a two level computational technique based on hierarchical approach is developed for load flow and optimal load flow calculations of large scale power systems. In the development of solution methods for optimal load flow and economic dispatch, nonlinear programming techniques are used.

A brief literature survey of the various models and techniques pertinent to these areas is now presented.

1.5 STATE OF THE ART

1.5.1 Load Flow

Load flow solution methods are well documented in the

literature [23,25,40] and can be classified into four categories,

1) Iterative methods employing Y_{BUS} - matrix or Z_{BUS} - matrix
2) Newton methods, 3) Decoupled methods, 4) Other methods.

The Gauss Seidel method [9] using Y_{BUS} - matrix offers advantages of simple problem formulation retaining sparsity. But it requires a large number of iterations for convergence and hence is slow computationally. Further, it presents convergence difficulties if the bus admittance matrix is not diagonally dominant, which may happen when the line configurations have capacitance. The method employing Z_{BUS} - matrix [1,6] with Gauss iterative scheme converges more reliably compared to Y_{BUS} - matrix method. Since Z_{BUS} - matrix is full, sparsity is lost. Further, additional time is needed to generate Z_{BUS} - matrix, To overcome this difficulty, various diakoptic, decomposition and piecewise methods primarily using Z_{BUS} [4,6,14,27] have been developed.

The Newton-Raphson method (NM) [2] together with sparsity and ordered elimination techniques [3] is a powerful method for obtaining load flow solutions. It uses the first two terms of the Taylor series expansion. The convergence of this method is fast and reliable. However, the main disadvantage of this method is its large computational requirements due to repeated calculation and triangulation of the Jacobian. Meisel and Barnard [12] gave the convergence

characteristics of the NM method and proposed the use of constant Jacobian for the load flow solution. The algorithm requires a larger number of iterations compared to NM and it may fail to converge for large systems. The methods proposed by Wallach et al [15] use rectangular coordinates and update the inverse of the Jacobian at every kth iteration by application of linear algebra which are not amenable to sparse matrix techniques. Several other variations of NM have also been reported [23,25,39]. Of late, there has been some interest in the second order load flow techniques. Sachdev and Medicherla [31] extended NM in polar coordinates with different variations to include upto the first three terms of the Taylor series expansion. This second order approach gives better accuracy and also there is some saving in computing time compared to NM. Iwamota and Tamura [40] used a constant Jacobian NM method in rectangular coordinates based on full Taylor series expansion. In this method of formulation, terms upto second order only are included in the Taylor series expansion of load flow equations, the higher order terms being zero. Although this method is claimed to be much faster than NM, it requires more memory space. Further, convergence difficulties have been reported by the authors using flat voltage start.

After 1970, decoupled methods have received attention for the fast a.c. load flow solution. These methods which solve

the MW- θ and MVAR-V problems separately, require approximately 40% less storage than NM and reduced computer time. Despotovic et al [16] developed a decoupled method in which direct solutions for the voltage magnitude and phase angle at the system buses are obtained. This method was later improved [28] with certain approximations. The matrix relating to the calculation of voltage magnitude correction is constant and the matrix relating to the calculation of phase angle correction needs re-calculation and re-triangulation at every iteration. A simultaneous-displacements iteration scheme is used which reduces the convergence characteristics of the method. Stott [19] presented a load flow method based on the decoupling principle, in which the polar current mismatch equation is utilized instead of the conventional MVAR mismatch equation to improve its convergence rate. It requires the calculation of coupling matrices at every iteration. Making further assumptions based on certain network properties, Stott and Alsac [29] developed a fast decoupled load flow technique. The final matrices are constant and hence the table of factors are to be obtained only once at the beginning of the iterative process. This method is now acknowledged to be superior to NM in terms of computational speed and storage. However, its convergence rate and accuracy are not better than NM. Recently, Berg et al [36] presented a method based on decoupling principles and successive approximation technique. Although its solution accuracy is similar to that of NM, the resulting matrices are not constant.

A variety of other load flow solution methods have also been reported. Wallach [7] and Sasson [10] used minimization techniques for load flow solution. These methods, which minimize an unconstrained scalar objective function usually equal to the sum of the squares of the current or power mismatches, are not best suited for routine load flow calculations. Dusonchet et al [17] proposed a method in which the load flow equations are divided into two groups. The first group corresponding to P-Q buses is solved by the generalized point Jacobi method, the second group corresponding to P-V buses by NM. This method achieves savings in storage and computational requirements compared to NM. Okamura et al [30] extended NM to include the effects of system control devices such as governors, exciters etc. Besides, flat and frequency bias tie line controls have also been discussed. Elangovan et al [34] presented an approximate load flow method based on reduction technique without exploiting sparsity. The method, however, does not take into account the Q-limit violations and its accuracy is good only if phase angles at the system buses are small.

1.5.2 Contingency Evaluation

The existing methods for contingency evaluation use sensitivity factors or load flows based on D.C. model, linearized A.C. model either full or decoupled and the constant matrix model. MacArthur [47] and Limmer [49] reported the use of sensitivity factors. The linear sensitivity factors known as

the distribution factors are generally derived from X_{BUS} - matrix. These factors cannot track the changing topological structure of the network and require periodic updating depending upon the operating state of the system. Moreover, computational and accuracy problems arise. D.C. load flow [51] is extremely fast and is comparatively better than distribution factors in accuracy. However, it gives only the solution of real powers and ignores actual voltage profile in assessing over loads. Daniel and Chen [55] developed a method similar to d.c. load flow using the changes in real power injection at the system buses to simulate a line outage. It does not provide any information regarding the reactive power flow. Contingency evaluation methods using A.C. load flow are available in Z_{BUS} as well as Y_{BUS} formulations.

Stagg and El-Abiad [48] investigated the use of Z-matrix for contingency evaluation which requires an excessive core storage. Brown [50,60] used Z-matrix axes discarding technique in order to conserve computer memory and to increase the speed of matrix formation for the determination of overloaded lines and low voltage caused by contingencies. These techniques are fast and suitable for simultaneous multiple outages but do not often yield accurate or complete information regarding the operating state of the power system.

The Gauss-Seidel method [46] can treat the changes in configuration very easily but its convergence is very poor.

The results obtained using the nonlinear load flow equations with NM [54] are very accurate but the computer time is excessive. Uemura [53] used constant matrices which are obtained by inverting the decoupled Jacobian matrix. Since, this method is not amenable to sparse matrix techniques, it needs excessive core storage and considerable computer time. Stagg and Phadke [52] presented an approach which uses the constant Jacobian NM method. The accuracy and speed of the method are not adequate. Sachdev and Ibrahim used sensitivity analysis in polar [58] as well as rectangular [61] formulations. These methods are fast and compute all the contingency states using base case factors of the Jacobian. However, some additional off-line computations for the suitable set of power injection modification factors are also needed. Pai and Khan [59] introduced a faster method based on sensitivity approach and linear models. Since the resulting matrices are non-symmetric, the method requires an increased memory storage. Tinney [56] proposed the use of a compensation method with triangular factorization to obtain sparse network solutions involving network outages. This led to the development of the well known competing methods due to Peterson [57] and Stott [29]. The linearized power flow model proposed by Peterson et al is based on the direct solution of a sparse system of linear network equations. Although this method is fast, it gives only an approximate solution. A separate A.C. load flow routine is required to obtain a full a.c. load flow solution.

Stott and Alsac proposed a fast decoupled algorithm using sparse triangular factors of the constant matrices. This is essentially a fast method and provides approximate as well as full a.c. load flow solutions.

1.5.3 Optimal Load Flow

A comparative study [67] and a comprehensive survey [73] of different optimization techniques for the solution of optimal load flow (OLF) have been made by Sasson et al and Happ respectively. To start with, Carpentier [64] formulated the general OLF problem which tried to meet the optimality relationships of Kuhn and Tucker. The method is slow and presents a convergence problem. Sasson [66] developed a sequential unconstrained minimization technique which presents convergence difficulties for large systems. Dommel and Tinney [65] proposed the use of Lagrangian multipliers and penalties to associate respectively the equality and inequality constraints to the objective function. The method uses NM for obtaining the load flow solution. The resulting reduced gradient is then used to find corrections for control vector. It is basically a first order method and is very sensitive to the selection of step lengths used at each gradient step. Alsac and Stott [72] used FDLP in the place of NM without changing the generality of formulation of Dommel and Tinney's approach to reduce memory storage and computer time. Sasson et al [68] used penalty functions for both equality and inequality constraints which are

added to the objective function. The augmented objective function is then minimized by using Hessian method possessing second order characteristics to update all the voltage magnitude and phase angle of buses. The convergence of this method is dependent upon the proper choice of values for the penalty factors. Further, the Hessian matrix is large and less sparse than the Jacobian matrix in NM and its structure is quite different from Y_{BUS} - matrix. Therefore, complex programming subroutines are needed to determine its configuration so that sparse matrix techniques can be employed. Rashed and Kelley [71] employed a second order approach to find corrections for the control vector. This is an improved version of Dommel and Tinney's method. Billinton and Sachdeva [69] used a sequential optimization approach in which the voltage magnitude is first optimized based on an assumed value of real power generation and then using the just optimized voltage variables, the real power generation is optimized. This iterative procedure is repeated until the improvements in the optimized variables are reduced below a certain tolerance level. Recently, Bala and Thanikachalam [74] proposed a method retaining the second order characteristics. An equivalent smaller sized matrix obtained from the original large sized Hessian matrix is used to update the control variables. Although this method is independent of the proper selection of step lengths, the computational requirements per iteration are more than in Dommel and Tinney's approach.

1.5.4 Economic Dispatch

Economic dispatch calculationsusing loss coefficients (B-coefficients) are in prevalent use for real time applications. Various techniques [75-77, 79] have been reported for the calculation of B-coefficients. Shoults et al [84] recently presented a method for the computation of B-coefficients based upon the method of least squares. It is accurate and efficient for solving economic dispatch problem for large interconnected systems. However, the above practice requires a re-computation of loss coefficients, whenever there is a significant change in the network. Alvarado [83] proposed a method for the calculation of incremental losses and penalty factors using the transposed sparsity oriented Newton-Raphson load flow Jacobian. This method is claimed to be faster compared to classical B-coefficients for large systems. Wadhwa and Nanda [81] presented a method in which economic coordination equations are solved by NM load flow technique to achieve better accuracy and speed, Alsac and Stott [80] used FDLP to compute penalty factors avoiding explicit Jacobian matrix. Malik and Rao [82] proposed the use of FDLP in the place of NM to solve the coordination equations. These methods, which employ FDLP, reduce the core storage and computer time, making it attractive for real-time applications.

1.5.5 Hierarchical Computation

There are few methods available in the literature pertaining to the application of hierarchical computation for solving the load flow and optimal load dispatch problems. Happ and Undrill [87] illustrated the basic features of multicomputer power flow computation using d.c. power flow solution. It is reported that this approach can also be extended to an a.c. load flow. Mitter and DyLiacco [85] proposed a two level optimization procedure which utilizes sequential unconstrained minimization technique to solve the first level optimization problem. Happ [86,96] explained how to dispatch real power economically through multicomputer configuration. This method is an extension of loss coefficients formulation in a multi-area case. Another paper by Happ [97] describes the multilevel piecewise theory for large network problems in a generalized manner. Recently, Irving et al [107] have presented their computational experience with decomposed state estimation and optimal real power dispatch based on hierarchical control theory. In this method, different linear programming techniques have been used for optimal real power control. It is reported that the solution times are realistic for online applications. Bielli et al [108] developed a method for real power economic dispatch based on the hierarchical approach. This method utilizes quadratic programming at the first level optimization and the coordination is achieved at the second

level by gradient type algorithms. In addition, the optimization of nondifferential functions and stochastic optimization have also been discussed. All these methods, however, consider only real powers for optimization. The control of other variables such as reactive powers and transformer tap ratios is ignored. Paranjothi [103] proposed a real and reactive power optimization procedure amenable to multi-computer configuration. It is reported by the author that the method presents convergence difficulties.

1.6 SCOPE AND OUTLINE OF THE THESIS

In this section, the main objectives of the thesis and a chapterwise summary are given :

The main objectives of the thesis are as follows :

i) Development of fast decoupled load flow technique in rectangular coordinates (FDLR), along the lines of polar version (FDLP) to improve the computing speed and its adaptation to contingency evaluation.

ii) Development of Newton-Richardson load flow solution method (NRM) - a powerful alternative method to NM and its adaptation to optimal load flow.

iii) Development of load flow solution method based on network reduction and NRM techniques (NETR), competitive to FDLP, in terms of computer time and memory storage for medium size systems and its adaptation to contingency evaluation and fast economic load dispatch.

iv) Development of two-level computational technique for large scale power system load flow and optimization based on hierarchical control concepts.

v) Theoretical study of the convergence characteristics of the new load flow solution methods.

A brief summary of the work reported in the thesis is given below :

In Chapter II, new load flow solution methods namely FDLR, NRM and NETR are developed.

FDLR is derived in two ways. Firstly, through linear transformation from FDLP and secondly direct from NM load flow equations in rectangular coordinates. The proposed algorithm is faster than FDLP for moderately accurate solutions.

NRM is obtained by combining the Chord method [12] and the Newton iterative method [13]. This is an attractive alternative method for systems where NM is preferred. The solution accuracy and convergence rate are practically the same as in NM, while the computing time is about 50% for large systems. It requires less storage and number of iterations for convergence compared to the recently developed method [40] in rectangular coordinates without truncation error.

NETR is developed using sparse matrix techniques based on

eliminating the P-Q buses and then applying the fast decoupled technique. The reduced system consisting of only P-V buses is solved by NRM. The method is fast, accurate and has good convergence properties. The solution accuracy is practically the same as in NM. A comparison with FDLP indicates both the competitive nature of the method and its suitability for on-line applications. The effectiveness of the proposed load flow algorithms is investigated on the IEEE 14 bus, 30 bus, 57 bus test systems and also on a heavily loaded 28 bus system. Besides, FDLR is also tested on a 133 bus system. A comparison of accuracy, speed and core storage requirements of these algorithms is made with FDLP and NM.

Chapter III deals with contingency evaluation using NETR and FDLR load flow algorithms developed in the previous chapter. The proposed techniques are very well suited for fast on or off-line outage security checks. As in prevalent competing methods [29,57], these techniques avoid the re-triangulation of the base case matrices for the simulation of different outage cases.

In NETR algorithm, the network outages are simulated using the matrix inversion lemma and the matrix updating algorithm. The technique is sufficiently accurate and is comparable to or faster than FDLP depending upon the number of P-V buses in the system. In FDLR algorithm, the network

outages are simulated with the help of the matrix inversion lemma. This rectangular version is faster and superior in accuracy for line flows greater than 50 MW compared to polar version i.e. FDLP.

Digital simulation of a number of network outage cases is carried out on the IEEE 14 bus, 30 bus and 57 bus test systems. The significant results of these system studies are presented and discussed in detail.

Chapter IV is devoted to the application of NRM and NETR load flow algorithms developed in Chapter II for optimal load flow and economic dispatch calculations respectively using the solution approach of Dommel and Tinney. The method of solution using NRM is faster in speed by more than 2 times compared to Dommel and Tinney's approach, without affecting the generality of formulation and convergence properties. The solution approach by NETR is based on two assumptions, 1) the voltage magnitude variations of the P-Q buses are not too sensitive to the real power changes, 2) the reactive power equations depend weakly on the phase angles of the voltages. This makes the algorithm competitive in terms of speed and core storage for real-time applications. Details of these solution algorithms are given. The proposed algorithms are tested on the adapted IEEE 14 bus, 30 bus and 57 bus test systems. A comparison of accuracy, speed and memory requirements of these proposed algorithms is made with Dommel and Tinney's approach.

Chapter V concerns itself with the development of load flow and optimal load flow methods for large scale power systems based on hierarchical concepts. A two level technique utilizing the formulation proposed by Haimes [104] is used. Additional pseudo variables are introduced to decouple the large scale system. The 1st level determines the subsystem solutions. The second level coordinates via pseudo variables. The computational advantages of sparse matrix techniques are used in the analysis of subsystems. Firstly, the multiarea load flow equations are given and solved by using NM, NRM, and FDLP. Then, the multiarea optimization problem is formulated as an additively separable non-linear programming problem by considering the real power generations, voltage magnitudes and transformer tap ratios as control variables, using the solution approach of Dommel and Tinney [65]. The effect of acceleration factor and the effect of number of subsystems over the rate of convergence are illustrated. Details of the optimal load flow solution algorithm considering both the equality and inequality constraints using the overall cost as the objective function are given. The effectiveness of the proposed two level technique is demonstrated by obtaining load flow and optimal load flow results for the adapted IEEE 30 bus and 57 bus test systems which are torn into 2 or 3 subsystems. A comparison of these results with those of the original untorn system is also made in terms of solution accuracy, storage space and overall computer time.

Chapter VI presents a theoretical study of the convergence characteristics of the new load flow solution techniques (FDLR, NRM, NETR) proposed in Chapter II. Each one of these load flow techniques is expressed suitably into the form of a general nonlinear iterative scheme. Then, the convergence conditions for these techniques are obtained by an application of the convergence theorem, used by Wu [33]. The validity of these conditions is checked on the IEEE 14 bus test system.

Chapter VII highlights the major contributions of the thesis. An assessment of the scope for further work is then made.

CHAPTER II

LOAD FLOW SOLUTIONS

2.1 INTRODUCTION

Many excellent methods [23,25,40] have been tested and published during the last 12 years to solve the problem of load flows for large scale power systems. A brief review and comparative study of the existing methods have been made in Section 1.5.1 of the preceding chapter. In this chapter, new load flow solution techniques, competitive to the prevalent methods are presented. The salient features of the proposed techniques are summarized as given below.

(1) Fast decoupled load-flow in rectangular coordinates (FDLR)

FDLR is developed via FDLP using linear transformation and also direct from NM load flow equations in rectangular coordinates. The final matrices turn out to be the same as in FDLP. A FDLR iteration is faster than that of a FDLP iteration, since trignometric functions do not have to be calculated. The existing FDLP program can be easily modified into FDLR. A comparison with FDLP indicates that FDLR is faster for moderately accurate solutions.

(2) Load flow solution by Newton-Richardson method (NRM)

NRM is a variant of NM based on the Chord and Newton-iterative techniques. The method offers an overall saving in

computing time of approximately 40 to 50% as compared to NM. The solution accuracy and the convergence rate are practically the same as in NM. The Jacobian is readily available for the important applications like optimal load dispatch, sensitivity analysis and security constrained optimization. The load flow program can be easily obtained from the existing NM program by adding a subroutine for the evaluation of minor iterates.

(3) Load flow solution by network reduction and Newton-Richardson techniques (NETR)

NETR is based on eliminating the P-Q buses and applying NRM to the P-V buses only, exploiting sparsity of the network. The method is comparable to FDLP in terms of computer time for medium size systems while the solution accuracy and convergence rate are similar to NM. It is very well suited for fast on-or off-line outage security checks and economic dispatch.

The proposed algorithms have been tested for the standard IEEE 14 bus, 30 bus and 57 bus systems, and also for a heavily loaded 28 bus system. FDLR algorithm has also been tested for a 133 bus system.

2.2 MATHEMATICAL FORMULATION OF THE PROBLEM

The basic problem is to determine the complex bus voltages in an A.C. transmission system for a prescribed set of constraints. Table 2.1 gives the classification of buses with pertinent information. It becomes necessary to choose one of

the available P-V buses as slack bus to take care of the system losses.

TABLE 2.1 CLASSIFICATION OF BUSES

Type of bus	Specified quantities	Unspecified quantities: Polar version	Unspecified quantities: Rectangular version
P-Q bus or load bus	1. real power consumed 2. reactive power consumed	1. voltage magnitude 2. voltage phase angle	1. real part of the voltage 2. imaginary part of the voltage
P-V bus or voltage controlled bus	1. voltage magnitude 2. real power 3. limits of reactive power	1. reactive power 2. voltage phase angle	1. reactive power 2. real part of the voltage 3. imaginary part of the voltage
Slack bus or swing bus or reference bus	For polar version: Voltage magnitude and phase angle For rectangular version: Real and imaginary parts of the voltage	1. real power 2. reactive power	1. real power 2. reactive power

2.2.1 Bus constraint equations

For the ith P-Q bus

$$P_{Gi}^{Sp} - P_{Li}^{Sp} - P_i = 0 \qquad (2.1)$$

$$Q_{Gi}^{Sp} - Q_{Li}^{Sp} - Q_i = 0 \tag{2.2}$$

where

$$P_i + j\, Q_i = E_i\, I_i^* = E_i \sum_{j=1}^{n} Y_{ij}^*\, E_j^*$$

For the ith P-V bus :

$$P_{Gi}^{Sp} - P_{Li}^{Sp} - P_i = 0 \tag{2.3}$$

$$V_i^{Sp} = (e_i^2 + f_i^2)^{\frac{1}{2}} = V_i \tag{2.4}$$

In concise vector form, the equations (2.1 - 2.4) can be represented as

$$[\, g([x]\;,\; [\hat{y}]\,)\,] = 0 \tag{2.5}$$

where $[x]$ = vector of all unspecified quantities

$[\hat{y}]$ = vector of all specified quantities

The load flow problem is therefore reduced to the numerical solution of the constraint equations (2.5) to find $[x]$ for a given $[\hat{y}]$. This basic problem gives only an unadjusted solution. However, an adjusted solution can be obtained by solving (2.5), subject to the reactive power, voltage magnitude and tap ratio constraints. The overall problem is non-linear in nature. Hence, iterative procedures are used to obtain the numerical solution.

2.3 DEVELOPMENT OF LOAD FLOW MODELS

2.3.1 Newton-Raphson Method (NM)

In this basic method, the solution of the non-linear load flow equation (2.5) is obtained by linearizing it using the Taylor series expansion in the neighbourhood of the initial estimates, neglecting the second and higher order terms. The polar or rectangular coordinates may be used for the bus voltages.

Polar Version :

The set of linearized equations in polar coordinates is represented in a matrix form as

$$[\, g([x]\ ,\ [\hat{y}]\ )^p] = [\, J^p\,]\ [\Delta x^p\,] \tag{2.6}$$

i.e.

$$\begin{bmatrix} \Delta P^p \\ \hline \Delta Q^p \end{bmatrix} = \begin{array}{c} (n_V+n_L) \\ (n_L) \end{array} \left[\begin{array}{c|c} [J_1^p] = [\frac{\partial P^p}{\partial \theta}] & [J_2^p] = [\frac{\partial P^p}{\partial V}] \\ \hline [J_3^p] = [\frac{\partial Q^p}{\partial \theta}] & [J_4^p] = [\frac{\partial Q^p}{\partial V}] \end{array}\right] \begin{bmatrix} \Delta\theta \\ \hline \frac{\Delta V}{V} \end{bmatrix}$$

$$\begin{array}{cc} (n_V + n_L) & (n_L) \end{array}$$

where

$$\Delta P_i^p = \text{real power mismatch for the ith P-V or P-Q bus}$$

$$= P_{Gi}^{Sp} - P_{Li}^{Sp} - V_i \sum_{j=1}^{n} ((G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})V_j) \tag{2.7}$$

ΔQ_i^p = reactive power mismatch for the ith P-Q bus

$$= Q_{Gi}^{Sp} - Q_{Li}^{Sp} - V_i \sum_{j=1}^{n} ((G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})V_j) \tag{2.8}$$

$\Delta\theta$, ΔV = bus voltage phase angle, magnitude corrections respectively.

$[J_i^p]_{i=1 \text{ to } 4}$ = submatrices of the Jacobian $[J^p]$

n_v = number of P-V buses in the system

n_L = number of P-Q buses in the system

and the superscript p refers to the polar coordinates. The elements of the Jacobian $[J^p]$ are defined in the Appendix A.

The linear equation (2.6) is solved for the corrections $[\Delta\theta]$ and $[\Delta V]$ to be applied to $[\theta]$ and $[V]$. Then,

$$[\theta]^{k+1} = [\theta]^k + [\Delta\theta]^k \tag{2.9}$$

$$[V]^{k+1} = [V]^k + [\Delta V]^k \tag{2.10}$$

The iterative calculations are repeated until the real and reactive power mismatches are within a specified convergence tolerance.

Rectangular Version :

The set of linearized equations in rectangular coordinates is given in a matrix form as

$$[g([x],\ [\hat{y}])^r] = [J^r]\ [\Delta x^r] \tag{2.11}$$

$$\text{i.e.}\ \begin{bmatrix} \Delta P^r \\ \hline \Delta Q^r \\ \hline \Delta V^2 \end{bmatrix} = \begin{array}{c} (n_V+n_L) \\ (n_L) \\ (n_V) \end{array} \left[\begin{array}{c|c} [J_1^r] = [\frac{\partial P^r}{\partial e}] & [J_2^r] = [\frac{\partial P^r}{\partial f}] \\ \hline [J_3^r] = [\frac{\partial Q^r}{\partial e}] & [J_4^r] = [\frac{\partial Q^r}{\partial f}] \\ \hline [J_5^r] = [\frac{\partial V^2}{\partial e}] & [J_6^r] = [\frac{\partial V^2}{\partial f}] \end{array}\right] \begin{bmatrix} \Delta e \\ \hline \Delta f \end{bmatrix}$$

$$\qquad\qquad (n_V+n_L) \qquad\qquad (n_V+n_L)$$

where

$$\Delta P_i^r = P_{Gi}^{Sp} - P_{Li}^{Sp} - \sum_{j=1}^{n} (e_i e_j + f_i f_j)G_{ij} + (f_i e_j - e_i f_j)B_{ij} \tag{2.12}$$

(for ith P-V and P-Q bus)

$$\Delta Q_i^r = Q_{Gi}^{Sp} - Q_{Li}^{Sp} - \sum_{j=1}^{n} (f_i e_j - e_i f_j)G_{ij} - (e_i e_j + f_i f_j)B_{ij} \tag{2.13}$$

(for ith P-Q bus)

ΔV_i^2 = square of the bus voltage magnitude corrections

(for ith P-V bus)

and the superscript r refers to the rectangular coordinates. The elements of the Jacobian submatrices $[J_i^r]_{i=1,2,\ldots 6}$ are given in the Appendix A.

Equations (2.6) or (2.11) have been solved for the correction vector by exploiting the sparsity of network admittance

and Jacobian matrices, through triangular factorization, compact storage and optimal renumbering of buses [3] which gives fast direct solutions at every iteration. However, NM is computationally inefficient, since it requires the factorization of the highly sparse [J] at every iteration. A number of modifications [25] including the recent second order models [31,40] are available in the literature to reduce the volume of computations.

2.3.2 Decoupled Methods

In all the decoupled methods [19,28,29,36], the load flow equations have been derived from NM to reduce the memory space and computing effort. These methods are based on neglecting the coupling submatrices $[J_2^p]$ and $[J_3^p]$ in equation (2.6) on the assumption that the coupling between the real power versus bus voltage magnitude and the reactive power versus bus voltage phase angle are relatively weak. Among the existing decoupled load flow methods, FDLP is simple, reliable and fast and is best suited for off or on-line applications. Its precise algorithmic form has been determined by extensive numerical studies. A theoretical study of its convergence characteristics has been reported later by Wu [33].

Fast decoupled load flow in polar coordinates (FDLP)

The final FDLP equations are given by

$$\left[\frac{\Delta P^p}{V}\right] = [B'] \, [\Delta\theta] \tag{2.14}$$

$$\left[\frac{\Delta Q^p}{V}\right] = [B''] \, [\Delta V] \tag{2.15}$$

where [B'] and [B''] are matrices of order $(n_V + n_L)$ and n_L respectively and can be obtained directly from the elements of [-B] with the following modifications [29]

i) omitting from [B'] the representation of network elements namely shunt reactances and off-nominal in-phase transformer taps.

ii) omitting from [B''] the angle shifting effects of phase shifters.

iii) neglecting series resistances in calculating the elements of [B'] which then becomes the d.c. approximation load flow matrix.

The real and sparse matrices [B'] and [B''] are constant. Hence, the table of factors are obtained only once at the beginning of the iterative process. Using these constant factors, very fast repeat solutions for $[\Delta\theta]$ and $[\Delta V]$ are obtained. The iterative procedure is repeated till the real and reactive power mismatches become small enough. Various storage schemes can be applied to take the advantage of sparsity and symmetry of [B'] and [B'']. However, [B'] is symmetrical only if the phase shifters are neglected.

2.4 FAST DECOUPLED LOAD FLOW IN RECTANGULAR COORDINATES (FDLR)

2.4.1 Derivation of FDLR from FDLP by linear transformation

The real and imaginary parts of the ith bus voltage in terms of its magnitude and angle are

$$e_i = V_i \cos \theta_i \; ; \quad f_i = V_i \sin \theta_i \tag{2.16}$$

By taking the exact differentials of the equation (2.16), we get,

$$\begin{bmatrix} \Delta e_i \\ \hline \Delta f_i \end{bmatrix} = \left[\begin{array}{c|c} -V_i \sin \theta_i & \cos \theta_i \\ \hline V_i \cos \theta_i & \sin \theta_i \end{array}\right] \begin{bmatrix} \Delta\theta_i \\ \hline \Delta V_i \end{bmatrix} \tag{2.17}$$

Inverting (2.17), we obtain

$$\begin{bmatrix} \Delta\theta_i \\ \hline \Delta V_i \end{bmatrix} = \left[\begin{array}{c|c} -\dfrac{\sin \theta_i}{V_i} & \dfrac{\cos \theta_i}{V_i} \\ \hline \cos \theta_i & \sin \theta_i \end{array}\right] \begin{bmatrix} \Delta e_i \\ \hline \Delta f_i \end{bmatrix} \tag{2.18}$$

Applying the transformation (2.18) in (2.14) and (2.15) and changing $[\Delta P]$ and $[\Delta Q]$ to rectangular coordinates, the following equations are obtained

$$\left[\frac{\Delta P^r}{V}\right] = [B'] \; [A_1' \; \vdots \; A_2'] \begin{bmatrix} \Delta e \\ \hline \Delta f \end{bmatrix} \tag{2.19}$$

$$\left[\frac{\Delta Q^r}{V}\right] = [B''] \; [A_1'' \; \vdots \; A_2''] \begin{bmatrix} \Delta e \\ \hline \Delta f \end{bmatrix} \tag{2.20}$$

where $[A_1']$, $[A_2']$, $[A_1'']$ and $[A_2'']$ are diagonal matrices with ii-th element given by

$$(A_1')_{ii} = -\frac{\sin \theta_i}{V_i}$$

$$(A_2')_{ii} = \frac{\cos\ \theta_i}{V_i}$$

$$(A_1'')_{ii} = \cos\ \theta_i$$

and $$(A_2'')_{ii} = \sin\ \theta_i$$

In the polar version, the voltage magnitude equations do not appear for the P-V buses. Hence, the equations (2.19) and (2.20) have to be augmented by

$$[\,\Delta V^2\,] = [\,A_1''' \;\;\vdots\;\; A_2'''\,] \begin{bmatrix} \Delta e \\ \hdashline \Delta f \end{bmatrix} \tag{2.21}$$

where $[\,A_1'''\,]$ and $[\,A_2'''\,]$ are diagonal matrices with ii-th element given by

$$(A_1''')_{ii} = 2\ e_i \quad ; \qquad (A_2''')_{ii} = 2\ f_i$$

On combining the equations (2.19 - 2.21) and making the same assumptions as made in FDLP, namely $V_i \simeq 1.0$ and $\theta_i - \theta_j \simeq 0$ and after some manipulations, we get

$$\begin{bmatrix} \Delta P_2^r \\ \cdot \\ \cdot \\ \Delta P_n^r \\ \hdashline \Delta Q_{m+1}^r \\ \cdot \\ \cdot \\ \Delta Q_n^r \\ \hdashline \Delta V_2^2 \\ \cdot \\ \cdot \\ \Delta V_m^2 \end{bmatrix} = \begin{bmatrix} [\,\hat{H}\,] & [\,\hat{L}\,] \\ \hdashline [\,\hat{M}\,] & [\,\hat{N}\,] \\ \hdashline [\,\hat{S}\,] & [\,\hat{T}\,] \end{bmatrix} \begin{bmatrix} \Delta e_2 \\ \cdot \\ \cdot \\ \Delta e_n \\ \hdashline \Delta f_2 \\ \cdot \\ \cdot \\ \Delta f_n \end{bmatrix} \tag{2.22}$$

$$[\hat{H}] = \left[\begin{array}{ccc:ccc} (-B'_{22}f_2) & \cdots & (-B'_{2m}f_m) & (-B'_{2,m+1}f_{m+1}) & \cdots & (-B'_{2n}f_n) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (-B'_{n2}f_2) & \cdots & (-B_{nm}f_m) & (-B'_{n,m+1}f_{m+1}) & \cdots & (-B'_{nn}f_n) \end{array}\right]$$

$$[\hat{L}] = \left[\begin{array}{ccc:ccc} (B'_{22}e_2) & \cdots & (B'_{2m}e_m) & (B'_{2,m+1}e_{m+1}) & \cdots & (B'_{2n}e_n) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (B'_{n2}e_2) & \cdots & (B'_{nm}e_m) & (B'_{n,m+1}e_{m+1}) & \cdots & (B'_{nn}e_n) \end{array}\right]$$

$$[\hat{M}] = \left[\begin{array}{ccc:ccc} 0 & \cdots & 0 & (B''_{m+1,m+1}e_{m+1}) & \cdots & (B''_{m+1,n}e_n) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & (B''_{n,m+1}e_{m+1}) & \cdots & (B''_{nn}e_n) \end{array}\right]$$

$$[\hat{N}] = \left[\begin{array}{ccc:ccc} 0 & \cdots & 0 & (B''_{m+1,m+1}f_{m+1}) & \cdots & (B''_{m+1,n}f_n) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & (B''_{n,m+1}f_{m+1}) & \cdots & (B''_{nn}f_n) \end{array}\right]$$

$$[\hat{S}] = \left[\begin{array}{ccc:ccc} 2e_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 2e_m & 0 & \cdots & 0 \end{array}\right]$$

$$[\hat{T}] = \left[\begin{array}{ccc:ccc} 2f_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 2f_m & 0 & \cdots & 0 \end{array}\right]$$

In the above derivation, the slack bus is numbered as 1, P-V buses as 2 to m and P-Q buses as m+1 to n. To achieve decoupling, the following further assumptions are made :

i) A flat voltage start ($e+jf = 1.0+j0.0$) is used.

ii) The matrices obtained using the flat voltage start are treated as constant at every subsequent iterative step. This avoids the re-calculation and re-triangulation of the Jacobian matrix at each iteration. The algorithm obtained, therefore, utilizes the fixed tangent slopes corresponding to the flat voltage start instead of the varying tangent slopes at each iteration.

With the above assumptions, equation (2.22) is reduced to the following set of decoupled equations in rectangular coordinates :

$$\begin{bmatrix} \Delta P_2^r \\ \cdot \\ \cdot \\ \cdot \\ \Delta P_n^r \end{bmatrix} = [B'] \begin{bmatrix} \Delta f_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta f_n \end{bmatrix} \qquad (2.23)$$

$$\begin{bmatrix} \Delta Q_{m+1}^r \\ \cdot \\ \cdot \\ \cdot \\ \Delta Q_n \end{bmatrix} = [B''] \begin{bmatrix} \Delta e_{m+1} \\ \cdot \\ \cdot \\ \cdot \\ \Delta e_n \end{bmatrix} \qquad (2.24)$$

$$\begin{bmatrix} \Delta V_2^2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta V_m^2 \end{bmatrix} = [B'''] \begin{bmatrix} \Delta e_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta e_m \end{bmatrix} \qquad (2.25)$$

where $[B'''] = 2[\hat{I}]$

Since $[\Delta f]$ and hence $[f]$ are known for the P-V buses from (2.23), $[e]$ for the P-V buses can be calculated using its specified voltage magnitude from

$$[e^2] = [V^2] - [f^2] \tag{2.26}$$

Replacing (2.25) by (2.26), the final FDLR equations become,

$$[\Delta P^r] = [B'] \quad [\Delta f] \tag{2.27}$$

$$[e] = ([V^2] - [f^2])^{\frac{1}{2}} \tag{2.28}$$

$$[\Delta Q^r] = [B''] \quad [\Delta e] \tag{2.29}$$

The above equations can also be obtained from NM load flow equations in rectangular coordinates as indicated below.

2.4.2 Derivation of FDLR from NM load flow equations

Using the flat voltage start tangent slopes at every iteration, the elements of the Jacobian in NM equations (2.11) $[J_i^r]_{i=1,2,\ldots 4}$ (vide Appendix A) are modified as follows :

$$\frac{\partial P_i^r}{\partial e_j} = -\frac{\partial Q_i^r}{\partial f_j} = G_{ij} \tag{2.30}$$

$$\frac{\partial P_i^r}{\partial f_j} = \frac{\partial Q_i^r}{\partial e_j} = -B_{ij} \tag{2.31}$$

$$\frac{\partial P_i^r}{\partial e_i} = \hat{a}_i + G_{ii} \tag{2.32}$$

$$\frac{\partial P_i^r}{\partial f_i} = \hat{b}_i - B_{ii} \tag{2.33}$$

$$\frac{\partial Q_i^r}{\partial e_i} = -\hat{b}_i - B_{ii} \tag{2.34}$$

$$\frac{\partial Q_i^r}{\partial f_i} = \hat{a}_i - G_{ii} \tag{2.35}$$

where

$$\hat{a}_i = \sum_{j=1}^{n} G_{ij} \tag{2.36}$$

$$\hat{b}_i = \sum_{j=1}^{n} B_{ij} \tag{2.37}$$

From equations (2.36 and 2.37), we may assume $\hat{a}_i << G_{ii}$ and $\hat{b}_i << B_{ii}$ and hence $\hat{a}_i$ and $\hat{b}_i$ can be neglected in equations (2.32 - 2.35). Further, neglecting G_{ij} and G_{ii} in the above expressions, equation (2.11) is reduced to

$$[\Delta P^r] = [B_p] \; [\Delta f] \tag{2.38}$$

$$[\Delta Q^r] = [B_Q] \; [\Delta e] \tag{2.39}$$

$$[\Delta V^2] = [B'''] \; [\Delta e] \tag{2.40}$$

where $[B_p]$ and $[B_Q]$ are the elements of $[-B]$ matrix. Changing the matrices $[B_p]$ and $[B_Q]$ to $[B']$ and $[B'']$ with the help of the modifications suggested in reference [29] and replacing (2.40) by (2.26), we get the final load flow equations in rectangular coordinates which are the same as obtained from FDLP by linear transformation in equations (2.27 - 2.29).

2.4.3 Iterative scheme

Equations (2.27 - 2.29) are solved successively using the most recent values. The best iteration strategy is termed as the (1f, 1e) scheme, which comprises one solution for $[\Delta f]$ using equation (2.27) to update $[f]$ relating to the P-V and P-Q buses, one solution for $[e]$ using equation (2.28) relating to the P-V buses and then one solution for $[\Delta e]$ using equation (2.29) to update $[e]$ relating to the P-Q buses. Iterations are repeated until the real and reactive power mismatches are within a specified convergence tolerance. In the solution of $[\Delta f]$ and $[\Delta e]$, the constant sparse triangular factors of $[B']$ and $[B'']$ are used. Interchanging equation (2.28) with equation (2.29) results in poor convergence.

2.4.4 Consideration of Q-limits of voltage controlled buses

To take into account the Q-limits of the voltage controlled buses, the following two methods can be used.

i) Method of switching P-V bus to P-Q bus and vice versa.

Each violated P-V bus is explicitly converted to a P-Q bus to fix the reactive power at the limiting value. The computations are done as for a P-Q bus and this requires the re-triangulation of [B"]. If in the subsequent computation, the reactive power falls within the available value, the bus is switched back to a P-V bus at the specified voltage.

ii) Method of sensitivity factor

The change in e_i at the ith violated P-V bus is calculated by using the sensitivity factor [29] given by

$$\Delta e_i = S_i \quad \Delta Q_i^r$$

This is used to reduce the error $Q_i = (Q_i^{limit} - Q_i)$ to zero. The sensitivity factor S_i may be computed by augmenting the existing factors of [B"] as indicated in Appendix B. This procedure does not require the re-triangulation of [B"].

2.5 LOAD FLOW SOLUTION BY NEWTON-RICHARDSON METHOD (NRM)

2.5.1 Derivation of NRM load flow equations

The basic idea of this method is to combine both the Chord method (or simplified NM [12]) and the Newton iterative method [13]. The linear set of equations appearing in NM has been represented in a matrix form in Section 2.3 (vide equation 2.6) as

$$[g([x], [\hat{y}])] = [J] [\Delta x] \qquad (2.41)$$

Let the Jacobian [J] at the kth step or major iteration be split as

$$[J]^{(k)} = \frac{1}{\alpha^{(k)}} [J]^{(0)} - [J_1]^{(k)} \tag{2.42}$$

where

$[J]^{(0)}$ = Jacobian evaluated using the initial bus voltage magnitude and phase angle estimates

$$[J_1]^{(k)} = \frac{1}{\alpha^{(k)}} [J]^{(0)} - [J]^{(k)}$$

and

α = real constant

Using this splitting, the Gauss-Seidel iteration for solving equation (2.41) at the kth major iteration is written as

$$\frac{1}{\alpha^{(k)}} [J]^{(0)} [\Delta x]^{(k)}_{i_o+1} = [J_1]^{(k)} [\Delta x]^{(k)}_{i_o} + [g([x], [\hat{y}])]^{(k)} \tag{2.43}$$

where the subscript i_o represents the minor iteration.

Combining (2.42) and (2.43) and simplifying, we get

$$\frac{1}{\alpha^{(k)}} [J]^{(0)} [\delta x]^{(k)}_{i_o} = - [J]^{(k)} [\Delta x]^{(k)}_{i_o} + [g([x], [\hat{y}])]^{(k)} \tag{2.44}$$

and

$$[\Delta x]^{(k)}_{i_o+1} = [\Delta x]^{(k)}_{i_o} + [\delta x]^{(k)}_{i_o} \tag{2.45}$$

A sequence of minor iterates $[\Delta x]_0^{(k)}$, $[\Delta x]_1^{(k)}, [\Delta x]_2^{(k)}$ ... $[\Delta x]^{(k)}$ is generated using equations (2.44) and (2.45) to approximate the solution of equation (2.41) at the kth major iteration in which $[\Delta x]_0^{(k)} = 0$.

The final converged value of $[\Delta x]^{(k)}$ at the kth major step is given as

$$[\Delta x]^{(k)} = [\delta x]_0^{(k)} + [\delta x]_1^{(k)} + [\delta x]_2^{(k)} + \dots \tag{2.46}$$

where

$$[\delta x]_0^{(k)} = \alpha^{(k)} [J]^{(0)^{-1}} \{ [g([x], [\hat{y}])]^{(k)} \}$$

$$[\delta x]_1^{(k)} = \alpha^{(k)} [J]^{(0)^{-1}} \{ [g([x], [\hat{y}])]^{(k)} - [J]^{(k)} [\delta x]_0^{(k)} \}$$

$$[\delta x]_2^{(k)} = \alpha^{(k)} [J]^{(0)^{-1}} \{ [g([x], [\hat{y}])]^{(k)} - [J]^{(k)} [[\delta x]_0^{(k)} + [\delta x]_1^{(k)}] \}$$

and so on.

A choice value of α between 0.0 and 2.0 is indicated in [37]. We have found that a value $\alpha = 1.0$ gives good results for the different cases studied.

2.5.2 Iterative schemes

Let $m_0^{(k)}$ be the number of terms included in equation (2.46) at the kth major iteration. Choosing $m_0 = 1$ and $\alpha = 1$ at each major iteration reduces the proposed method to the Chord or simplified NM method. The numerical results based on three iterative schemes depending on the value of $m_0^{(k)}$ at each major

iteration have been considered in Section 2.7. Table 2.2 gives the pertinent information regarding the three schemes.

TABLE 2.2 ITERATIVE SCHEMES OF NRM

k	m_o		
	Scheme I	Scheme II	Scheme III
1	1	1	1
2	2	3	2
3	2	3	3
4	2	3	4
5	2	3	5
.	.	.	.
.	.	.	.

The Q-limit violations of the voltage controlled buses can be handled by using a similar sensitivity factor approach as indicated in Section 2.4.4 and Appendix B.

2.6 LOAD FLOW SOLUTION BY NETWORK REDUCTION AND NEWTON-RICHARDSON TECHNIQUES (NETR)

2.6.1 Derivation of NETR load flow algorithm

We have the general equation

$$[I] = [Y]\,[E] \tag{2.47}$$

The bus admittance matrix [Y] is assembled in such a manner that the first n_G buses represent the voltage controlled buses including the slack bus and the last n_L buses represent the load buses.

The equivalent load admittance at bus i is given by

$$Y_{Li} = \frac{P_{Li}^{Sp} - j\, Q_{Li}^{Sp}}{V_i^2} \tag{2.48}$$

If at each load bus, the scheduled complex load power is represented by the equivalent admittances, then the vector equation (2.47) gets modified to

$$[\,I\,] = [Y'] \; [\,E\,] \tag{2.49}$$

i.e.

$$\left[\begin{array}{c} [I_G] \\ \hline [0] \end{array}\right] = \left[\begin{array}{c|c} [\,Y_{GG}\,] & [\,Y_{GL}\,] \\ \hline [\,Y_{LG}\,] & [\,Y'_{LL}\,] \end{array}\right] \left[\begin{array}{c} [\,E_G\,] \\ \hline [\,E_L\,] \end{array}\right]$$

and

$$[Y'_{LL}] = [Y_{LL}] + [D_L\,] \tag{2.49a}$$

where

$[\,Y_{LL}\,]$ = load bus admittance matrix before adding the equivalent load admittances.

$[\,D_L\,]$ = diagonal matrix representing the equivalent load admittances.

From (2.49), we get

$$[I_G] = \{[Y_{GG}] - [Y_{GL}]\ [Y'_{LL}]^{-1}\ [Y_{LG}]\}\ [E_G] \tag{2.50}$$

$$[E_L] = -\ [Y'_{LL}]^{-1}\ [Y_{LG}]\ [E_G] \tag{2.51}$$

Equations (2.50) and (2.51) can be written as

$$[I_G] = [Y'_{GG}]\ [E_G] \tag{2.52}$$

$$[Y'_{LL}]\ [E_L] = -\ [Y_{LG}]\ [E_G] \tag{2.53}$$

where $[Y'_{GG}]$ represents the bus admittance matrix of an equivalent system consisting of only voltage controlled buses and the slack bus. $[Y'_{GG}]$ is obtained by Kron's reduction process, which essentially consists in applying Gaussian elimination to the modified bus admittance matrix $[Y']$, exploiting the sparsity of the network as explained in [21,24]. At the end of the reduction process, the form of the modified bus admittance matrix $[Y']$ is shown in the accompanying Fig. 2.1. The reduction process provides the triangular factors of $[Y'_{LL}]$ matrix in addition to the non-triangularized equivalent admittance matrix $[Y'_{GG}]$ as indicated in Fig. 2.1.

Let

$$[Y'_{GG}] = [G_R] + j\,[B_R] \tag{2.54}$$

The well known polar power mismatch NM is applied to an equivalent system consisting of only voltage controlled buses. By

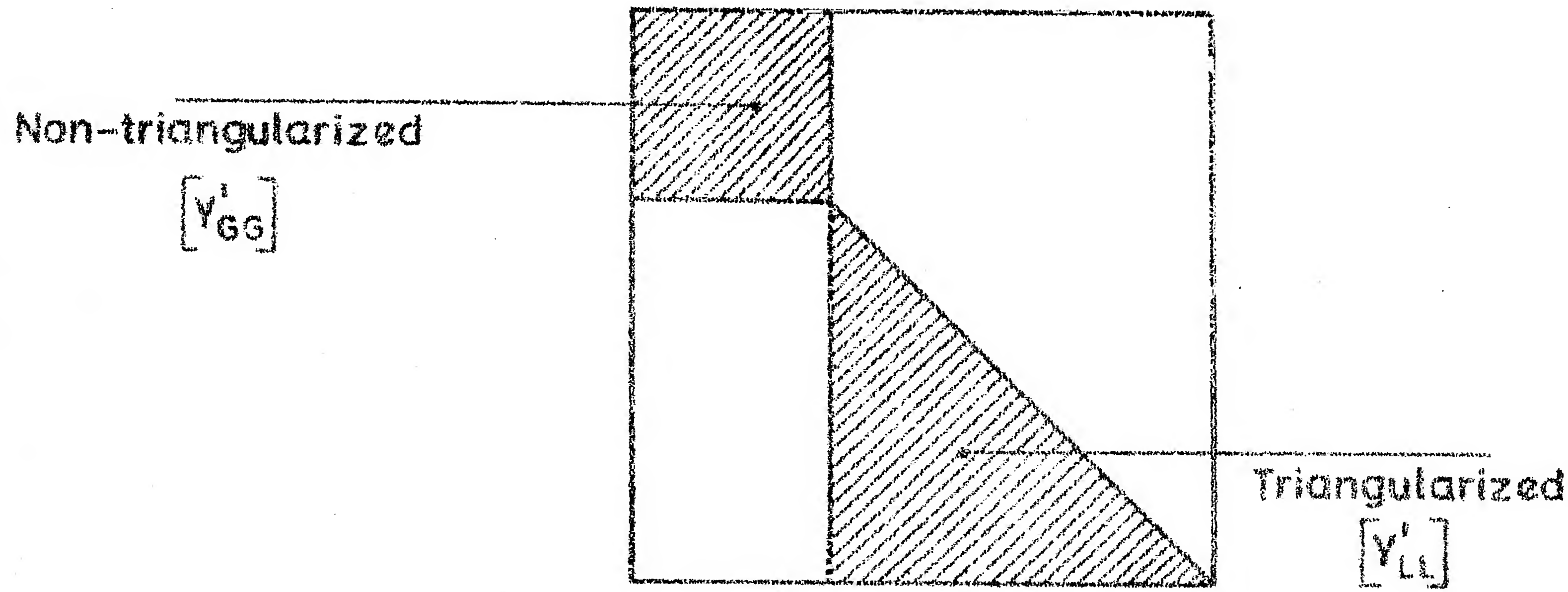


FIG. 2.1 FORM OF MODIFIED BUS ADMITTANCE MATRIX $[Y']$ AT THE END OF REDUCTION PROCESS

approximating the resulting Jacobian with the help of the valid assumptions [29] namely, $\cos\theta_{ij} \approx 1$ and $G_{Rij}\sin\theta_{ij} << B_{Rij}$, we get

$$\left[\frac{\Delta P_v}{V_v}\right] = [B'_R]\,[\Delta\theta_v] \tag{2.55}$$

where the elements of $[B'_R]$ are strictly the elements of $[-B_R]$

ΔP_{vi} = real power mismatch at the bus i relating to an equivalent system consisting of only voltage controlled buses and the slack bus

$$= P^{Sp}_{Gi} - P^{Sp}_{Li} - V_i \sum_{j=1}^{n_G} (V_j(G_{Rij}\cos\theta_{ij} + B_{Rij}\sin\theta_{ij}))$$

and

$[\Delta\theta_v]$ = voltage phase angle correction vector relating to the voltage controlled buses.

The final load flow equations are represented by equations (2.55) and (2.53). The technique to solve for $[\Delta\theta_v]$ from equation (2.55) is by NRM (vide Section 2.5) without triangularizing $[B'_R]$ at every iteration.

Let $[B'_{Ro}]$ be the matrix obtained during the first iteration. Then, the final converged value for $[\Delta\theta_v]$ at each iteration k is expressed in a series form as

$$[\Delta\theta_v]^{(k)} = [\delta\theta_v]_o^{(k)} + [\delta\theta_v]_1^{(k)} + [\delta\theta_v]_2^{(k)} + .. \quad (2.56)$$

where

$$[\delta\theta_v]_o^{(k)} = [B'_{Ro}]^{-1}\{ [\frac{\Delta P_v}{V_v}] \}$$

$$[\delta\theta_v]_1^{(k)} = [B'_{Ro}]^{-1}\{ [\frac{\Delta P_v}{V_v}] - [B'_R]^{(k)} [\delta\theta_v]_o^{(k)} \}$$

and so on.

The experimental studies indicate that it is only necessary to include the first two terms of the series given by (2.56) i.e. NRM Scheme I (vide Section 2.5) for the same solution accuracy, as obtained by the direct triangularization of $[B'_R]$. Hence, each solution of $[\Delta\theta_v]$ from equation (2.56) requires two repeat solutions using the factors of $[B'_{Ro}]$.

2.6.2 Iterative algorithm

The basic iterative algorithm for the proposed method is as follows :

1) Read the system data and initial estimates of the bus voltages (magnitude and angle).
2) Form the bus admittance matrix $[Y]$ using the network elements and shunt elements except loads.
3) Obtain the equivalent load admittances corresponding to the scheduled complex load powers using equation (2.48) and modify $[Y]$ to get $[Y']$.

4) Obtain the equivalent bus admittance matrix $[Y'_{GG}]$ by reduction process and hence $[B'_R]$.

5) Obtain the correction $[\Delta\theta_V]$ using NRM Scheme I (equation 2.56) and determine the new values of the complex voltages relating to the voltage controlled buses.

6) Obtain the load bus voltages using the triangular factors of $[Y'_{LL}]$ available from step (4) in equation (2.53).

7) Steps (3) to (6) represent one complete iteration. Iterations are repeated until the exact solution is obtained, i.e. when

$$\max_i |\Delta P_{vi}| < \varepsilon_t$$

The speed of computation can be further increased by a modification described below.

2.6.3 Modified form of NETR

The above algorithm requires more computing time than FDLP due to the necessity of reducing the modified bus admittance matrix $[Y']$ at each iteration, even though, the total number of iterations are less for moderately accurate solutions (mismatch of 1 MW). To reduce the computation

time significantly, in every alternate iteration, the changes in $[D_L]$ matrix in equation (2.49a) due to the changes in load bus voltages are neglected for the calculation of $[\Delta\theta_V]$. However, the changes in $[D_L]$ matrix for the calculation of the load bus voltages from equation (2.53) can be incorporated by writing it as follows.

$$[Y'_{LL}]\,[E_L] = [\Delta D_L]\,[E_L] - [Y_{LG}]\,[E_G] \tag{2.57}$$

where the change in $[D_L]$ is represented by

$$[\Delta D_L] = [D_L]_{old} - [D_L]_{new} \tag{2.58}$$

This allows the old triangular factors of $[Y'_{LL}]$ to be used in the calculation of $[E_L]$.

2.6.4 Consideration of Q-limits of voltage controlled buses

Each violated voltage controlled bus is explicitly converted into a load bus, so that the Q-limit is held at its specified value. If a P-V bus is switched to a P-Q bus, then an extra row and column is eliminated from $[Y'_{GG}]$ relating to the switched bus in order to obtain a new equivalent system consisting of only non-violated voltage controlled buses. The complete reduction of $[Y']$ matrix is not necessary once again at any iteration due to the violation of voltage controlled buses. If in the subsequent iteration, the reactive power falls, within the specified limit, the bus is switched back as a P-V bus at the specified voltage.

2.7 NUMERICAL RESULTS ON TEST SYSTEMS AND COMPARISON

The proposed load flow methods outlined in Sections 2.4 to 2.6 have been tested by computing the load flows for the following power system examples on DEC 1090 system.

1. IEEE 14 bus test system
2. IEEE 14 bus test system with R/X ratio of the heavily loaded line increased by 5 times
3. IEEE 30 bus test system
4. IEEE 57 bus test system
5. 28 bus heavily loaded system [38]

The specifications of the above systems are given in Appendix D. In addition, FDLR has also been tested on a 133 bus system given in reference [22].

The results obtained from the load flow solutions on these systems using the flat voltage start are listed in Tables 2.3 to 2.10. Details regarding the max $|\Delta P|$ and max $|\Delta Q|$ for each iteration are given in Tables 2.3 to 2.6. The number of iterations and the relative CPU time in % are shown in Tables 2.7 to 2.9. Tables 2.3 to 2.9 pertain to unadjusted solutions (no Q-limits imposed) so as to compare the convergence characteristics of the proposed load flow techniques, whereas Table 2.10 corresponds to adjusted solutions with the consideration of Q-limits. For the consideration of the Q-limit violations in FDLP and FDLR, method 1, discussed in Section 2.4.4 is used. For comparison, the load flow results obtained using

TABLE 2.4 MISMATCHES DURING NM, NRM, FDLP, FDLR AND NETR LOAD FLOW SOLUTIONS

IEEE 30 BUS SYSTEM

MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	Convergence characteristics									
	Max $\|\Delta P\|$ mismatch p.u.					Max $\|\Delta Q\|$ mismatch p.u.				
	iter.0	1	2	3	4	0	1	2	3	4
NM	0.9316	0.0593	0.0002	-	-	0.5671	0.0638	0.0033	-	-
FDLP	0.9316	0.1795	0.0041	-	-	0.8111	0.0443	0.0003	-	-
FDLR	0.9316	0.1952	0.0255	0.0098	-	0.5702	0.1237	0.0169	0.0024	-
NETR	1.0398	0.0398	0.0005	-	-	-	-	-	-	-
Modified NETR	1.0398	0.0441	0.0110	0.0009	-	-	-	-	-	-
NRM I	0.9316	0.0593	0.0009	-	-	0.5671	0.0638	0.0028	-	-
NRM II	0.9316	0.0593	0.0005	-	-	0.5671	0.0638	0.0032	-	-
NRM III	0.9316	0.0593	0.0009	-	-	0.5671	0.0638	0.0028	-	-

TABLE 2.5 MISMATCHES DURING NM, NRM, FDLP, FDLR AND NETR LOAD FLOW SOLUTIONS
IEEE 57 BUS SYSTEM
MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	Convergence characteristics									
	Max $\|\Delta P\|$ mismatch p.u.					Max $\|\Delta Q\|$ mismatch p.u.				
iter.	0	1	2	3	4	0	1	2	3	4
NM	2.8654	0.0438	0.0082	-	-	1.7198	0.1439	0.0084	-	-
FDLP	2.8654	0.2358	0.0124	0.0024	-	1.8893	0.0511	0.0026	-	-
FDLR	2.8654	0.3321	0.0723	0.0142	0.0069	1.8963	0.1284	0.0423	0.0081	-
NETR	2.5186	0.0415	0.0018	-	-	-	-	-	-	-
Modified NETR	2.5186	0.0476	0.0254	0.0008	-	-	-	-	-	-
NRM I	2.8654	0.0438	0.0120	0.0015	-	1.7198	0.1439	0.0494	0.0085	-
NRM II	2.8654	0.0438	0.0084	-	-	1.7198	0.1439	0.0194	0.0006	-
NRM III	2.8654	0.0438	0.0120	0.0007	-	1.7198	0.1439	0.0494	0.0031	-

TABLE 2.6 MISMATCHES DURING FDLR AND FDLP LOAD FLOW SOLUTION

133 BUS SYSTEM [22]

MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Iteration No.	Max |ΔP| mismatch in p.u.		Max |ΔQ| mismatch in p.u.	
	FDLP	FDLR	FDLP	FDLR
0	4.2852	4.2852	26.3119	26.2690
1	2.2161	2.0897	0.1732	0.1885
2	0.1060	0.0445	0.0085	0.0127
3	0.0070	0.0022	-	0.0020

TABLE 2.8 COMPUTATIONAL COMPARISON BETWEEN FDLR AND FDLP

133 BUS SYSTEM [22]

MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	No. of iterations	Relative computer time in % on DEC 1090 system
FDLP	3	100
FDLR	3½	96

TABLE 2.7a COMPUTATIONAL COMPARISON BETWEEN FDLP, FDLR AND NETR LOAD FLOW SOLUTIONS

MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	IEIE 14 bus		IEEE 30 bus		IEEE 57 bus	
	No.of iterations	Relative computer time in % on DEC 1090 system	No.of iterations	Relative computer time in % on DEC 1090 system	No.of iterations	Relative computer time in % on DEC 1090 system
FDLP	3	100	$2\frac{1}{2}$	100	3	100
FDLR	3	86	$3\frac{1}{2}$	93	4	88
NETR	2	81	2	102	2	105
Modified NETR	3	81	3	95	3	95

TABLE 2.7b COMPUTATIONAL COMPARISON BETWEEN FDLP, FDLR AND NETR LOAD FLOW SOLUTIONS MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	IEEE 14 bus system with R/X ratio of line 1 increased by 5 times		28 bus system [38] (heavily loaded)	
	No.of iterations	Relative computer time in % on DEC 1090 system	No.of iterations	Relative computer time in % on DEC 1090 system
FDLP	10 (14θ , 6V)	100	8	100
FDLR	12 (14f, 10e)	74	11	87
NETR	3	51	3	166
Modified NETR	4	49	3	105

TABLE 2.9 COMPUTATIONAL COMPARISON BETWEEN NM AND NRM LOAD FLOW SOLUTIONS
MISMATCH < 0.001 P.U. MW AND 0.001 P.U. MVAR

System	NM		NRM					
			Scheme I		Scheme II		Scheme III	
	No. of iterations	Relative computer time in % on DEC 1090 system	No. of iterations	Relative computer time in % on DEC 1090 system	No. of iterations	Relative computer time in % on DEC 1090 system	No. of iterations	Relative computer time in % on DEC 1090 system
IEEE 14 bus	3	100	3	94	3	100	3	97
IEEE 14 bus with R/X ratio of line (1) increased by 5 times	3	100	4	112	3	107	3	100
28 bus system [38] (heavily loaded)	8	100	8 (2 NR + 6 NRM)	67	8 (2 NR + 6 NRM)	83	8 (2 NR + 6 NRM)	98
IEEE 30 bus	3	100	3	72	3	85	3	76
IEEE 57 bus	3	100	5	78	3	64	4	79

TABLE 2.10 CONSIDERATION OF Q-LIMITS

IEEE 30 BUS SYSTEM

MISMATCH < 0.1 MW AND 0.1 MVAR

Method	No. of iterations	Relative computer time in % on DEC 1090 system
FDLP	$4\frac{1}{2}$	100
FDLR	$6\frac{1}{2}$	105
NETR	4	117

NM and FDLP are also included. The same ordering and programming techniques are used for all these methods. The value of $\alpha^{(k)} = 1$ is used for NRM load flow solution.

Based on the results shown in Tables 2.3 to 2.10, the comments and comparisons made with respect to the proposed load flow techniques are given below.

A. Comments on FDLR and its comparison with FDLP

1) The simulation time required per iteration of FDLR is smaller than the corresponding iteration of FDLP.

2) Although FDLR takes more number of iterations for convergence as compared to FDLP, the total computer time is less by about 5 to 10 percent for all the test systems (no Q-limits imposed)

3) For the IEEE 14 bus system with R/X ratio of the heavily loaded line increased by 5 times, the saving in computer time by FDLR is more than 20 percent.

4) For the heavily loaded 28 bus system given in reference [38], with some of the phase angles at the system buses of the order of -55°, both FDLR and FDLP took considerably more number of iterations for convergence and the saving in computer time by FDLR is about 13%.

5) With 2 buses violating their Q-limits on the IEEE 30 bus system, FDLR took 2 iterations more than FDLP. However, the total computer time is comparable with FDLP.

B. Comments on NRM and its comparison with NM

1) The rate of convergence is adjustable and depends on the value of m_o^k.

2) The solution accuracy and the convergence rate of Scheme II are similar to those of NM.

3) The computational time required by all the schemes is less than by NM and it decreases, as the size of the system increases. For the IEEE 57 bus system, the computational time saving is 36 percent.

4) It is known that in NM, the convergence rate is not affected when R/X ratio of the transmission line is increased. This was also found to be true in NRM, when R/X ratio of the heavily loaded line was increased by 5 times in the IEEE 14 bus system.

5) For the heavily loaded 28 bus system, with some of the bus angles at the system buses of the order of -55°, it is essential to use NRM after two initial NM iterations to obtain successful convergence.

C. Comments on NETR and its comparison with FDLP

1) The solutions are sufficiently accurate in 2 or 3 iterations for all the test systems. The number of iterations is not seen to be a function of the total number of buses. The total computing time is more as compared to FDLP, but is much less as compared to NM.

2) The convergence rate is not affected on the IEEE 14 bus system, with R/X ratio of the heavily loaded line increased by 5 times and also on a heavily loaded 28 bus system.

3) The modified form of the algorithm which ignores the changes in load bus voltages in alternate iterations in the calculation of $[\Delta \theta_V]$ is efficient, faster and requires comparable or less computing times compared to FDLP.

4) The total simulation time is comparable to FDLP, on the IEEE 30 bus system with two buses violating their Q-limits.

2.8 CONCLUSION

In this chapter, three new load flow solution methods have been presented, viz. 1) fast decoupled method in rectangular coordinates possessing distinct computational advantages over

the polar version, 2) Newton-Richardson method, an improved version of NM and 3) network reduction method, a comparable alternative to the fast decoupled method for medium size systems. The FDLR and NETR can be easily extended for rapid contingency evaluation needed in power system security assessment as shown in the next chapter. Besides, NRM and NETR load flow algorithms can be efficiently adapted respectively for optimal load flow and economic dispatch calculations as illustrated in Chapter IV. These methods have been tested on the IEEE 14 bus, 30 bus, 57 bus test systems plus a heavily loaded 28 bus system and a 133 bus system.

CHAPTER III

CONTINGENCY EVALUATION

3.1 INTRODUCTION

In Chapter I, we presented the basic security concepts and the various security related functions. The key function of the security analysis is known as contingency evaluation which identifies, whether the normal system is secure or insecure. A number of fast on-line approximate algorithms [29,57-59] have been proposed for contingency evaluation. The work reported in this area along with a critical review of the pertinent literature has been presented in Chapter I (Section 1.5.2). The techniques used for contingency evaluation must possess the essential features of fast computational speed, reliability, reasonable accuracy and moderate memory storage requirements. The objective of this chapter is to extend NETR & FDLR load flow techniques developed in the preceding chapter for contingency evaluation. The proposed techniques make use of only base case factors for the simulation of different contingencies. Detailed solution algorithms using the proposed techniques are given for implementation purposes. The proposed algorithms have been verified by simulation on the IEEE 14 bus, 30 bus and 57 bus test systems. A comparision of the proposed methods, and a competitive method, FDLP is made in

terms of solution accuracy, core storage and computational requirements.

3.2 STATEMENT OF THE PROBLEM

Contingency evaluation consists of two parts. Firstly, it determines the steady state solution of the nonlinear load flow equations due to the assumed network and/or power outages as classified in Table 3.1. Secondly, it analyses the results for different constraint violations like transmission line and transformer power flows, reactive power and bus voltage limits. The thesis is mainly concerned with the first part of the problem, which can be restated as follows :

Given : the base case load flow solution of the system along with the contingency list.

To determine : the post contingency states of the system.

TABLE 3.1 CLASSIFICATION OF OUTAGES

Type of outage	System status
Network	i) outage of a transmission line
	ii) outage of a transformer
	iii) outage of a shunt capacitor or reactor
Power	i) loss of a generator
	ii) sudden loss of a load
	iii) sudden change in flow in inter-tie

3.2.1 Contingency List

Since it is very difficult to test a large power system for every conceivable disturbance, a suitable contingency list is generally created based on the statistical analysis of past occurrences, off-line simulation studies etc. The contingency list can be prepared in a systematic way to contain only the cases pertaining to the present state of the system. It should be updated frequently according to the new information available. More recently, Ejebe and Wollenberg [62] have proposed a fast technique for automatic ranking and selection of contingency cases. The algorithm developed, ranks the line and generator outage cases according to the severity of their effects on bus voltages or line flows using the d.c. load flow as well as nonlinear a.c. load flow equations.

3.3 CONTINGENCY EVALUATION BY NETWORK REDUCTION AND NEWTON-RICHARDSON TECHNIQUES

3.3.1 Development of solution technique

For the evaluation of network outage between the voltage controlled buses including the slack bus termed as type-1, only 4 elements of the base case $[Y'_{GG}]$ and hence of $[B_R]$ and $[B'_R]$ (vide Chapter II, Section 2.6) are changed. If the outage occurs between the buses i and j, then the change in the reduced matrix $[Y'_{GG}]$ is

$$[\Delta Y'_{GG}] = \begin{array}{c|cc} & i & j \\ \hline i & -y_{ij} - y_{io} & y_{ij} \\ j & y_{ij} & -y_{ij} - y_{jo} \end{array} \qquad (3.1)$$

where

y_{io}, y_{jo} = line charging capacitance and shunt branches of the off-nominal transformer equivalent circuit lumped at nodes i and j

Hence, $[Y'_{GG}]$ and $[B'_R]$ are modified as,

$$[Y'_{GG}]_{new} = [Y'_{GG}] + [\Delta Y'_{GG}] \qquad (3.2)$$

$$[B'_R]_{new} = [B'_R] + b_v [M_v]^T [M_v] \qquad (3.3)$$

where

$$b_v = b_{ij}$$

and

$[M_v]$ is a highly sparse vector given by

$$\begin{array}{c} \qquad\qquad\quad i \qquad\qquad\quad j \\ [0,0,\ \ldots,\ 1,0,\ \ldots\ -1,0,\ \ldots\ 0] \end{array} \qquad (3.4)$$

If the network outage involves the removal of an off-nominal transformer, then $[M_v]$ vector becomes

$$\begin{array}{c} \qquad\qquad i \qquad\qquad\qquad j \\ [0,0,\ \ldots\ \frac{1}{t_{ij}},\ 0,\ \ldots\ -1,0,\ \ldots\ 0] \end{array} \qquad (3.5)$$

By using the inversion of a modified matrix method (vide Appendix B), the correction for $[\Delta\theta_v]$ is obtained as,

$$- a_v [X_v] [M_v] [\Delta\theta_v] \tag{3.6}$$

where

$$[X_v] = [B'_R]^{-1} [M_v]^T \tag{3.7}$$

and

$$a_v = (\frac{1}{b_v} + [M_v][X_v])^{-1} \tag{3.8}$$

For each network outage of type 1, the non-sparse vector $[X_v]$ is determined using the factors of $[B'_R]$ in equation (3.7). After each solution of $[\Delta\theta_v]$ using equation (2.55), it is corrected by an amount using equation (3.6). After one or two iterations, depending on the needed accuracy, the load bus voltages are determined using equation (2.53).

When the network outage occurs between a load bus and any other bus or between the load buses termed as type-2, $[Y'_{LL}]$ itself changes in equation (2.49). Without going through the reduction process once again, $[Y'_{GG}]$ and hence $[B'_R]$ is obtained using the matrix updating algorithm proposed by Smith [21] (vide Appendix B) which makes use of the base case factors only.

$[\Delta\theta_v]$ in equation (2.55) is solved by NRM-Scheme I (vide Chapter II, Section 2.5) with two repeat solutions using the factors of $[B'_R]$ relating to the base case. Further,

since $[Y'_{LL}]$ also changes at the maximum by 4 elements, the load bus voltages are determined using the inversion of a modified matrix method.

After the solution of (2.53), $[E_L]$ is corrected by an amount

$$= - a_L [X_L] [M_L] [E_L] \qquad (3.9)$$

where

$$[X_L] = [Y'_{LL}]^{-1} [M_L]^T \qquad (3.10)$$

$$a_L = \left(\frac{1}{y_L} + [M_L][X_L]\right)^{-1} \qquad (3.11)$$

and

$$y_L = -y_{ij}$$

Details of the derivation of vectors $[M_V]$ and $[M_L]$ and scalars a_V and a_L are given in the Appendix B.

3.3.2 Implementation

The technique described in the preceding section for contingency evaluation is now given in the form of a detailed algorithm for implementation purposes.

Iteration scheme

Two iteration strategies with different speed and accuracy are proposed. In scheme I, termed as $(1\theta_V, 1E_L)$ scheme, first θ_V - iteration is performed using equation (2.55) followed by E_L - iteration using equation (2.53). This is found to work well for most of the outages. However, for the

outage of a very heavily loaded line, scheme II termed as $(2\theta_v, 1E_L)$ scheme is proposed. In this scheme, which gives better accuracy, $2\theta_v$ - iterations are performed first and then followed by one E_L - iteration.

Preliminary step

We perform load flow solution for the base case and store the triangular factors of $[B_R']$, $[Y_{LL}']$, the factors needed for the matrix updating algorithm, the matrix $[Y_{GG}']$ and the converged bus voltage vector. For on-line studies, the bus voltage vector may be obtained from the state estimator and the different matrices may be easily built and factorized. At the end of the base case load flow solution, the table of factors and the various matrices are stored as shown in the accompanying Fig. 3.1.

The main steps involved in the iterative solution are listed below :

A. For a network outage between voltage controlled buses including the slack bus - type 1.

1. Obtain $[\Delta Y_{GG}']$ using equation (3.1) and form $[Y_{GG}']_{new}$.
2. Compute the mismatch $\left[\frac{\Delta P_v}{V_v}\right]$
3. Compute $[\Delta\theta_v]$ by a repeat solution using the base case factors of $[B_R']$ in equation (2.55)
4. Compute the correction for $[\Delta\theta_v]$ using equation (3.6)

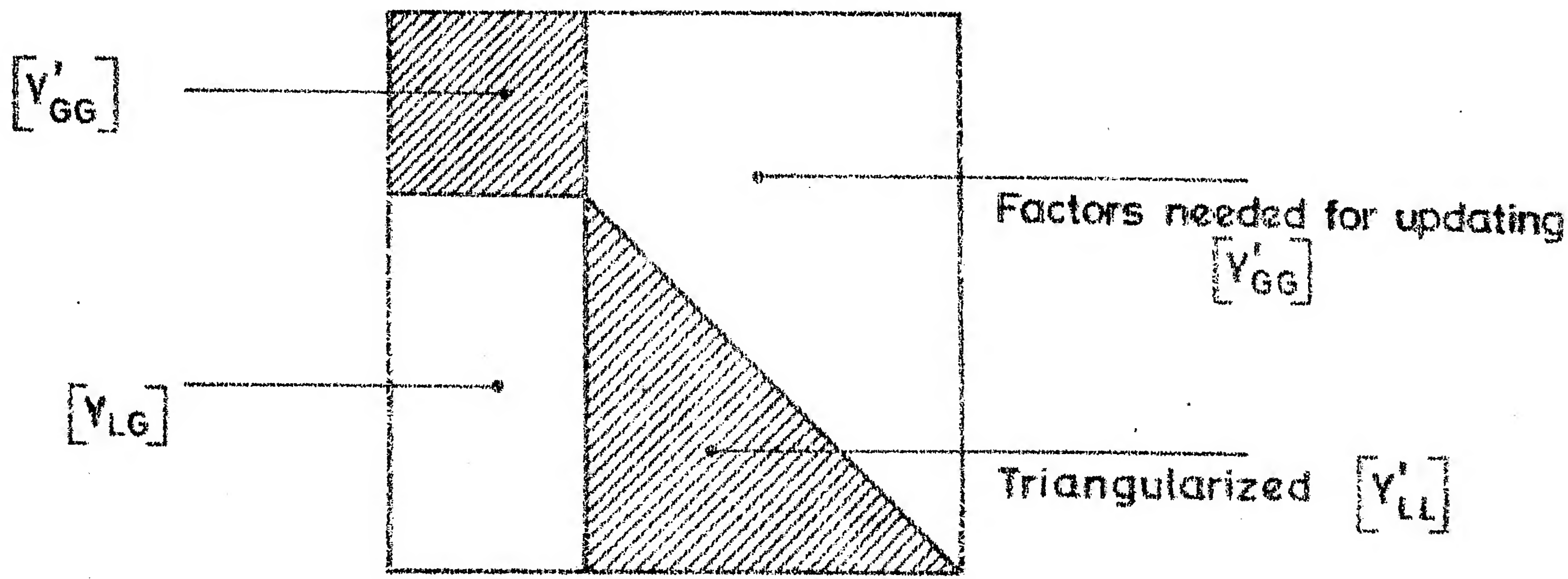


FIG. 3.1 STORAGE OF DIFFERENT MATRICES AT THE END OF BASE CASE LOAD FLOW SOLUTION.

5. For $(1\theta_V, 1E_L)$ scheme, proceed to the next step. For $(2\theta_V, 1E_L)$ scheme compute the mismatch using the new values of $[\theta_V]$ and repeat steps (3) and (4) and proceed to step (6).
6. Compute $\{-[Y_{LG}][E_G]\}$ and solve for $[E_L]$ using equation (2.53)
7. Repeat steps (1) to (6) for each network outage of the above type to be simulated.

B. For a network outage between a load bus and any other bus or between load buses - Type - 2.

1. Obtain $[\Delta Y'_{GG}]$ using the matrix updating algorithm and form $[Y'_{GG}]_{new}$ and hence $[B'_R]_{new}$
2. Compute the mismatch $[\frac{\Delta P_V}{V_V}]$
3. Compute $[\Delta\theta_V]$ by NRM - scheme - I by two repeat solutions using the base case factors of $[B'_R]$ and update the angles $[\theta_V]$
4. For $(1\theta_V, 1E_L)$ scheme, proceed to the next step. For $(2\theta_V, 1E_L)$ scheme, compute the mismatch using the new values of $[\theta_V]$ and repeat step (3) and proceed to step (5).
5. Compute $\{-[Y_{LG}][E_G]\}$ and solve for $[E_L]$ using equation (2.53)
6. Obtain the correction for $[E_L]$ using equation (3.9) and update the voltage vector $[E_L]$ obtained from step (5).

7. Repeat steps (1) to (6) for each network outage of the above type to be simulated.

C. Power outage

1. Redistribute the power lost according to the generator distribution factors and proceed to step (7). If it is not possible to do it, proceed to the next step.
2. The real power generation lost is automatically distributed to all the other regulating generators on the basis of their capacities and governor droops based on the steady-state frequency drop of the power system.
3. Compute the new mismatch $[\frac{\Delta P_V}{V_V}]$
4. Compute $[\Delta\theta_V]$ using equation (2.55) and update the angles $[\theta_V]$
5. For $(1\theta_V, 1E_L)$ scheme, proceed to the next step. For $(2\theta_V, 1E_L)$ scheme, repeat steps (3) and (4) and continue.
6. Compute $\{-[Y_{LG}][E_G]\}$ and solve for $[E_L]$ using equation (2.53)
7. Repeat steps (1) to (7) for each power outage to be simulated.

3.3.3 Solution speed and storage

A realistic comparison is made in Tables 3.2 and 3.3 for the major computing operations to be performed for the simulation of outages using the proposed method and the FDLP.

TABLE 3.2 MAJOR COMPUTING OPERATIONS NEEDED FOR θ (FDLP) AND θ_V (NETR) - ITERATION

Operation	FDLP $(1\theta, 1V)$	FDLP $(2\theta, 2V)$	Proposed- NETR $(1\theta_V, 1\ E_L)$	Proposed- NETR $(2\theta_V, 1E_L)$
Base case matrix to be built and factorized	$[B']$ $(n_s x n_s)$	$[B']$ $(n_s x n_s)$	$[B'_R]$ $(n_V x n_V)$	$[B'_R]$ $(n_V x n_V)$
Matrix to be updated per type-2 outage only	-	-	$[B'_R]$	$[B'_R]$
Number of mismatch computations per outage	1	2	1	2
Number of repeat solutions per outage	2	3	2	3 or 4

The following comments are made from the Tables 3.2 and 3.3.

The schemes $(1\theta, 1V)$ and $(1\theta_V, 1E_L)$ require the same number of mismatch computations and repeat solutions. The $(2\theta_V, 1E_L)$ scheme needs one mismatch computation and one repeat solution less than the $(2\theta, 2V)$ scheme. The proposed schemes require computing operations for updating the matrix $[B'_R]$ for every type-2 outage. The arithmetic calculations needed for $\{-[Y_{LG}][E_G]\}$ computation relating to the proposed schemes are less than the corresponding mismatch computation

TABLE 3.3 MAJOR COMPUTING OPERATIONS NEEDED FOR V (FDLP) AND E_L (NETR) ITERATION

Operation	FDLP $(1\theta, 1V)$	FDLP $(2\theta, 2V)$	Proposed - NETR $(1\theta_v, 1E_L)$	Proposed - NETR $(2\theta_v, 1E_L)$
Base case matrix to be built and factorized	$[B'']$ $(n_L x n_L)$	$[B'']$ $(n_L x n_L)$	$[Y'_{LL}]$ $(n_L x n_L)$	$[Y'_{LL}]$ $(n_L x n_L)$
Number of mismatch computations per outage	1	2	-	-
Number of $\{-[Y_{LG}]\ [E_G]\}$ computations per outage	-	-	1	1
Number of repeat solutions per outage	2	3	2	2

requirements of the FDLP schemes. Further, the total computing time needed for θ_v - iteration relating to the proposed schemes depends on the number of P-V buses in the system, since θ_v - iteration is performed on the reduced system consisting of only P-V buses.

A numerical comparison reveals :

i) For type-2 outage, the proposed method is faster than FDLP, if the number of P-V buses is less than about 10% of the total number of buses in the system.

ii) For type-1 outage, the proposed method does not require the updating of $[B'_R]$. Hence, the reduction in time as given in (i) is increased by about two times.

The matrices involved in the proposed method are symmetric and hence, only the upper or lower triangular factors need to be stored for carrying out repeat solutions similar to FDLP.

3.4 CONTINGENCY EVALUATION BY FAST DECOUPLED TECHNIQUE IN RECTANGULAR COORDINATES

3.4.1 Development of solution technique

With the help of the inversion of a modified matrix method, (vide Appendix B) network outages like lines or transformers are simulated. This method avoids the re-triangulation of the network matrices $[B']$ and $[B'']$ for the simulation of single or multiple outage cases. Experimental studies indicate that it is only necessary to simulate the removal of series transmission elements from these matrices. However, all the changes must be correctly taken into account in the calculation of active and reactive power mismatch vectors.

For each network outage involving lines or transformers, two vectors $[X']$ and $[X'']$ are calculated in the following manner.

$$[X'] = [B']^{-1} [M']^T \tag{3.12}$$

$$[X''] = [B'']^{-1} [M'']^T \tag{3.13}$$

where $[M']$ and $[M'']$ are highly sparse row vectors each containing one or two non-zero elements (vide equations 3.4 and 3.5).

After each solution of equation (2.27), $[\Delta f]$ is compensated by an amount

$$- a'[X'][M'][\Delta f] \qquad (3.14)$$

Similarly, after each solution of equation (2.29), $[\Delta e]$ is compensated by an amount

$$- a''[X''][M''][\Delta e] \qquad (3.15)$$

where

$$a' = \left(\frac{1}{b'} + [M'][X']\right)^{-1}$$

$$a'' = \left(\frac{1}{b''} + [M''][X'']\right)^{-1}$$

and

b', b'' = susceptances of the outaged line or transformer.

There is no correction needed for the equation (2.28). Details of the derivation of vectors $[X']$ and $[X'']$ and scalars a' and a'' are given in Appendix B.

3.4.2 Iterative algorithm for outage simulation

A. Base case load flow

1. Read the input system data and initial estimates for $[e]$ and $[f]$
2. Form the bus admittance matrix $[Y]$

3. Obtain [B'] and [B"] from [Y] using the approximations and modifications suggested in reference [29] (vide Chapter II, Section 2.3.2) and store its table of factors
4. Obtain the base case solutions [e_o] and [f_o] by iterating the equations (2.27 - 2.29) successively until the convergence is reached and store it.

B. Network outage

1. Initiate the base case solution
2. Form the vectors [M'] and [M"] corresponding to the outage case and solve the equations (3.12 and 3.13) to obtain [X'] and [X"]
3. Compute [ΔP^r] using equation (2.12) and solve for [Δf] by a repeat solution using equation (2.27).
4. Compute the correction for [Δf] using equation (3.14) and update [f]
5. Compute [e] relating to the P-V buses using equation (2.28)
6. Compute [ΔQ^r] using equation (2.13) and solve for [Δe] relating to the P-Q buses by a repeat solution using equation (2.29)
7. Check whether the network outage is between P-V buses including the slack bus. If it is, proceed to step (9). Otherwise, continue to the next step.
8. Compute the correction for [Δe] using equation (3.15)

9. Update [e]
10. For (1f, 1e) scheme, proceed to the next step.
    For (2f, 2e) scheme, repeat steps (3) to (9) and continue.
11. Repeat steps (1 to 10) for each network outage to be simulated.

C. Power outage

The power outage can be simulated based on the similar lines described in Section (3.3. 2-C).

3.5 NUMERICAL RESULTS ON TEST SYSTEMS AND COMPARISON

The IEEE 14 bus, 30 bus and 57 bus test systems (system specifications are given in Appendix D) were used for contingency evaluation with the proposed NETR and FDLR techniques and the details of the results are compiled in Tables 3.4 and 3.5. The number of line/transformer outages simulated in the three test systems were 19,26 and 35 respectively using ($1\theta_V$, $1E_L$), ($2\theta_V$, $1E_L$), (1f, 1e) and (2f, 2e) schemes of the proposed methods and (1θ, 1V) and (2θ, 2V) schemes of FDLR. All the line and transformer outages were considered for the 14 bus test system, excepting line 10, whose outage splits the system into two networks. Most of the lines selected for the other systems were heavily loaded. Table 3.4 gives the line real power flows for a most heavily loaded single line outage in IEEE 57 bus test system using the proposed methods as well as FDLP. The exact results obtained by NM load flow

TABLE 3.4 COMPARISON OF LINE REAL POWER FLOWS > 50 MW FOR A MOST HEAVILY LOADED SINGLE LINE OUTAGE

IEEE 57 BUS TEST SYSTEM

Line No.	Between buses From	To	NM load flow	FLLP $(1\theta, 1V)$	FLLP $(2\theta, 2V)$	FDLR $(1f, 1e)$	FDLR $(2f, 2e)$	NETR $(1\theta_V, 1E_L)$	NETR $(2\theta_V, 1E_L)$
			Outage of line 8-9	Real power flow in MW					
1	1	2	75.30	69.19	73.21	68.31	72.92	64.30	73.70
2	2	3	71.26	67.05	69.12	65.03	68.82	61.50	69.32
5	4	6	56.01	48.97	55.16	50.77	55.75	58.89	56.43
6	6	7	61.51	57.85	61.06	58.80	61.58	61.97	62.13
7	6	8	110.17	106.92	109.91	105.50	110.14	110.36	110.40
8	8	9		OUT OF SERVICE					
13	13	14	52.91	46.19	51.10	46.25	51.43	49.98	52.47
14	13	15	94.55	86.24	92.18	87.01	93;16	90.35	93.88
15	1	15	163.36	152.39	159.79	151.11	160.13	150.70	160.31
16	1	16	102.38	95.59	100.30	94.97	100.39	96.81	100.91
17	1	17	116.31	109.89	114.47	109.11	114.48	110.85	114.94
18	3	15	112.77	105.12	111.59	106.69	112.69	114.02	111.78
22	7	8	189.66	177.75	180.66	172.88	180.55	180.60	180.46
24	11	13	53.82	46.28	51.85	47.09	52.85	50.08	53.12
26	12	16	54.40	48.20	52.52	47.49	52.36	49.58	53.31
27	12	17	69.49	63.23	67.59	62.66	67.59	64.61	68.33
28	14	15	107.36	99.53	105.02	100.70	106.32	103.02	105.88
41	7	29	114.41	118.94	114.98	128.02	115.46	113.88	113.60
67	29	52	50.51	44.18	49.88	42.55	49.62	49.58	49.77

TABLE 3.5 COMPARISON OF AVERAGE AND MAXIMUM ERRORS IN REAL POWER FLOWS (IEEE 14 BUS, 30 BUS AND 57 BUS TEST SYSTEMS)

Method	IEEE 14 bus system No. of contingencies simulated = 19			IEEE 30 bus system No. of contingencies simulated = 26			IEEE 57 bus system No. of contingencies simulated = 35		
	Average error in %	Maximum error in %	Relative computer time in % on DEC 1090	Average error in %	Maximum error in %	Relative computer time in % on DEC 1090	Average error in %	Maximum error in %	Relative computer time in % on DEC 1090
FDLP $(1\theta, 1V)$	1.52	13.38	100	1.14	13.36	100	1.20	14.01	100
FDLR $(1f, 1e)$	1.36	11.61	34	1.13	15.60	90	1.28	15.76	95
NETR $(1\theta_v, 1E_L)$	1.53	8.57	92	1.75	11.10	94	1.56	14.60	93
FDLP $(2\theta, 2V)$	0.47	8.15	142	0.21	4.47	149	0.20	3.66	155
FDLR $(2f, 2e)$	0.43	10.80	111	0.52	6.05	128	0.42	7.53	145
NETR $(2\theta_v, 1E_L)$	0.73	8.09	99	0.69	6.04	98	0.78	11.30	96

are also given for comparison purposes. Table 3.5 shows the average error for the overall study and the highest of the maximum error observed for the different schemes. Besides, the relative CPU time in % is also given. In the analysis of average and maximum error, lines with less than 50 MW flow were not considered. The base case solution was used to start the outage calculation for the proposed as well as FDLP methods. Based on the representative results given in Tables 3.4 and 3.5, the following observations are made.

1. Overall simulation time of the proposed ($1\theta_V$, $1E_L$) scheme is slightly faster than the (1θ, $1V$) scheme of FDLP. Simulation times are considerably reduced with the proposed ($2\theta_V$, $1E_L$) scheme compared to the (2θ, $2V$) scheme. The percent reduction in computer time becomes greater as the number of buses in the system increases. Although the average error obtained by using the ($2\theta_V$, $1E_L$) scheme is slightly higher than the (2θ, $2V$) scheme, it is still less than the acceptable limit of 1 percent. This shows that fast and reasonably accurate solutions can be obtained by the proposed NETR method.

2. The proposed FDLR technique takes about 10 to 20 percent less computer time compared to FDLP. The average and maximum errors in line real power flows for the overall study using the proposed (1f, 1e) scheme are comparable to or better than those obtained from (1θ, $1V$) scheme of FDLP. These values are slightly more for the proposed (2f, 2e) scheme compared to the (2θ, $2V$) scheme of FDLP.

3.6 CONCLUSION

In this chapter, we have presented two methods for contingency evaluation. Method I is based on eliminating the load buses using sparse matrix techniques. This method has definite savings in computation time compared to FDLP if the number of P-V buses in the system is less than about 10% of the total number of buses. It requires more memory storage than FDLP due to the requirement of the storing of factors needed for updating the matrix $[B_R']$. However, this additional storage is not a limiting factor, since sparsity is exploited. Method II is based on the fast decoupled technique in rectangular coordinates. In comparison with FDLP, it requires 10 to 20% less computer time. The core storage requirement is the same as in FDLP. Network outage cases are simulated using the proposed methods in one or two iterations with an average error in real power flows less than 1%. These methods have been tested on the IEEE 14 bus, 30 bus and 57 bus systems on DEC 1090 system.

CHAPTER IV

OPTIMAL LOAD FLOW SOLUTIONS AND ECONOMIC DISPATCH

4.1 INTRODUCTION

The optimal load flow (OLF) is a constrained nonlinear programming problem. The OLF and the simplified economic dispatch problems have been discussed in Chapter I (Section 1.3). The methods reported for OLF are based on Kuhn-Tucker theorem [64], Lagrange multipliers [65,71], Hessian matrix [68] and reduced Hessian matrix [74] possessing second order characteristics. The various methods [80-83] proposed for economic dispatch mainly differ in the calculation of penalty factors. A brief review of these methods pertaining to OLF and economic dispatch has been made respectively in Sections 1.5.3 and 1.5.4.

The objective of this chapter is twofold. The first is to utilize the NRM load flow technique developed in Chapter II for OLF solution in the method of Dommel and Tinney [65]. This approach avoids the re-triangulation of the Jacobian matrix at each load flow iteration and hence considerable saving in computer time is achieved. Then, the NETR load flow technique developed in Chapter II is used for economic dispatch. The optimization is carried out on an equivalent system consisting of only P-V buses. It uses the

constant factors of the Jacobian matrix relating to the reduced system. Therefore, it is fast, and competitive to the existing methods [80,82] using FDLP and is very attractive for real time applications.

The proposed methods have been tested on the adapted IEEE 14 bus, 30 bus and 57 bus systems and the results are compared with those obtained by Dommel and Tinney's method [65] in terms of solution accuracy and overall computing times.

4.2 STATEMENT OF THE PROBLEM

The variables and parameters of the power system have been separated into unspecified and specified quantities represented by [x] and $[\hat{y}]$ respectively, in Chapter II (Section 2.2.1). Some of the specified variables $[\hat{y}]$ are adjustable. Hence the vector $[\hat{y}]$ can be partitioned as $[\hat{y}] = \left[\begin{array}{c} [u] \\ \hline [p] \end{array}\right]$ where [u] is the control vector and [p] is the vector of fixed parameters.

Thus, the power system variables and parameters are grouped into three categories as summarized below :

1. State vector or dependent vector [x]. This consists of the voltage angles of P-V and P-Q buses and the voltage magnitude of P-Q buses.
2. Control vector or independent vector [u]. This constitutes the adjustable real power generation available for optimum dispatch, voltage magnitude of generator buses and transformer tap ratios.

3. Constant or specified vector $[p]$. This consists of the constant load power, specified generator reactive power and other constant network parameters.

The general OLF problem can be stated as a mathematical programming problem given by,

Minimize the scalar objective function,

$F([x], [u])$ subject to

i) Equality constraints imposed upon the system by load flow equations (vide Chapter II, Section 2.2.1)

$$[g([x], [u], [p])] = 0 \qquad (4.1)$$

ii) Inequality constraints on some parameters of the form

$$[u^{min}] \leq [u] \leq [u^{max}] \qquad (4.2)$$

$$[h^{min}] \leq [h] \leq [h^{max}] \qquad (4.3)$$

where h is the compact representation for functional inequality constraints.

The objective function may be the overall cost of production or total system losses. For minimizing the cost of production, the objective function takes the form,

$$F([x], [u]) = \sum_{j=1}^{n_p} (a_{oj} + b_{oj} P_{Gj} + c_{oj} (P_{Gj})^2) \qquad (4.4)$$

For optimal reactive power flow, the objective function is the total system loss and is given by

$$F([x], [u]) = P_{Gs}([x], [u]) \tag{4.5}$$

where P_{Gs} refers to the slack bus real power generation.

4.3 OPTIMAL LOAD FLOW SOLUTION BY NEWTON-RICHARDSON TECHNIQUE

The OLF problem stated in the preceding section can be solved efficiently by Dommel and Tinney's method [65]. In this method, the load flow equations are solved by NM, which requires the calculation of the table of factors of the Jacobian at each load flow iteration. In this section, the application of NRM (vide Chapter II, Section 2.5) is proposed in the place of NM. The proposed method differs in two aspects from the method of Dommel and Tinney.

1) The table of factors of the Jacobian obtained at the end of initial load flow are treated as constant during the subsequent load flows.

2) The equations pertaining to the load flow and Lagrange multipliers are solved by using NRM.

4.3.1 Method of solution

Firstly, the inequality constraints are not considered. Then, the Lagrangian function is formed by introducing as many auxiliary variables (otherwise known as Lagrange multipliers) as there are equality constraints in (4.1) and it is given as

$$L = F([x], [u]) + [\lambda]^T [g([x], [u], [p])] \quad (4.6)$$

where $[\lambda]$ = vector of Lagrange multipliers.

Optimality criterion :

The necessary conditions for the minimum of F, while satisfying the equality constraints $[g]$ are,

$$[L_\lambda] = [\frac{\partial L}{\partial \lambda}] = [g([x], [u], [p])] = 0 \quad (4.7)$$

$$[L_x] = [\frac{\partial L}{\partial x}] = [\frac{\partial F}{\partial x}] + [\frac{\partial g}{\partial x}]^T [\lambda] = 0 \quad (4.8)$$

$$[L_u] = [\frac{\partial L}{\partial u}] = [\frac{\partial F}{\partial u}] + [\frac{\partial g}{\partial u}]^T [\lambda] = 0 \quad (4.9)$$

The set of non-linear simultaneous equations (4.7 to 4.9) is solved by iterative solution technique to obtain the optimal solutions.

4.3.2 NRM solution procedure

The solution algorithm proceeds as follows :

Step 1 : Start the iteration count for the gradient step $k = 1$

Step 2 : Read the system data. Assume a starting value for the control vector $[u]$ and for the unspecified voltage phase angles and magnitudes.

Step 3 : Check if $k > 1$. If it is, proceed to step (5); otherwise continue to the next step.

Step 4 : Solve the load flow equations (4.7) by NRM for the state vector $[x]$. Obtain the table of factors of the Jacobian matrix corresponding to the converged solution and store it. Proceed to step (6).

Step 5 : Solve the load flow equations in (4.7) by NRM making use of the table of factors available from step (4). Proceed to step (7).

Step 6 : Solve the equation (4.8) for $[\lambda]$ by a repeat solution using the table of factors available from step (4). Proceed to step (8).

Step 7 : Solve the equation (4.8) for $[\lambda]$ by NRM making use of the factors available from step (4). This requires 2 repeat solutions for NRM - scheme I.

Step 8 : At this point ($[x]$, $[u]$, $[\lambda]$), compute the reduced gradient vector $[L_u]$ from equation (4.9).

Step 9 : If $[L_u]$ is sufficiently small, indicating that no further improvement in the objective function is possible through the control of $[u]$ and therefore the minimum is reached. At the minimum, the gradient vector components will be

$$L_{ui} = 0 \quad \text{if} \quad u_i^{min} \leq u_i \leq u_i^{max}$$

$$L_{ui} \leq 0 \quad \text{if} \quad u_i = u_i^{max}$$

$$L_{ui} \geq 0 \quad \text{if} \quad u_i = u_i^{min}.$$

Otherwise, proceed to the next step.

Step 10 : Adjust the control vector u in the negative gradient direction using the formula

$$[u^{k+1}] = [u^k] + [\Delta u^k] \tag{4.10}$$

$$[\Delta u^k] = - \beta^k \; [L_u^k] \tag{4.11}$$

Advance the iteration count $k = k + 1$ and return to step (3). β is a scalar and is known as step length.

4.3.3 Determination of step length β

The critical part of the solution algorithm given above is step (10). The computational efficiency and convergence characteristics are sensitive to the determination of the step length in the negative gradient direction. The step lengths are calculated at each ~~succeeding~~ gradient steps k by using a steepest descent algorithm [72] as described below.

Step 1 : Compare the signs of L_{ui}^k and L_{ui}^{k-1}. If they are equal, then $\beta_i^k = 1.5 \quad \beta_i^{k-1}$.

Step 2 : Otherwise, compute the inverse Hessian matrix diagonal element $\hat{h}_{ii}$ to interpolate the optimum value which has been overshot due to the reversed direction of the gradient component

$$\hat{h}_{ii} = (u_i^{k-1} - u_i^k)/(L_{ui}^{k-1} - L_{ui}^k)$$

(b) Functional inequality constraints

These are inequality constraints except those on the independent or control variables and are taken into account by the penalty function method. In this method, the objective function is augmented by a function of the violated constraints, i.e.

$$F([x], [u]) = F_o([x], [u]) + \sum_{j \varepsilon \hat{m}} R_j \qquad (4.13)$$

where F_o is the original objective function; $\hat{m}$ is the set of all violated constraints and R_j is the penalty for each of the violated functional constraints

$$\begin{aligned} R_j &= \gamma_j (h_j - h_j^{max})^2 \quad \text{if} \quad h_j > h_j^{max} \\ &= \gamma_j (h_j^{min} - h_j)^2 \quad \text{if} \quad h_j < h_j^{min} \end{aligned} \qquad (4.14)$$

where γ is the penalty factor.

The main difficulty in this method is the selection of suitable values for the penalty factors which influences the convergence characteristics and solution accuracy. To alleviate this difficulty, a variable penalty factor approach as indicated in reference [74] can be used. In this approach γ_j may be considered as a function of the iteration count. To start with, a small value is chosen and then successively larger values are employed and this gives more weight to the objective function in the first few iterations. The larger value of the penalty factor used, as the solution is

approached, increases the weight on the minimization of the penalty function.

4.4 ECONOMIC LOAD DISPATCH SOLUTION BY NETWORK REDUCTION TECHNIQUE

The load flow solution by network reduction technique (NETR) developed in Chapter II (Section 2.6) is used for fast economic load dispatch.

4.4.1 Economic load dispatch

Here, the objective function is the production cost as given by the equation (4.4). The control vector $[u]$ consists of only controllable real power generations. Other control variables are assumed to be fixed.

Problem statement

Determine $[u_p]$ (real power generation) which minimizes the objective function $F([x], [u])$ subject to

i) load flow equation

$$[g([x], [u], [p])] = 0$$

ii) limits on control variables $[u_p]$

The functional inequality constraints are not considered.

4.4.2 Method of solution

The real and reactive power balance equations (load flow equations) are solved for the initial assumed scheduling of real power generation and the converged solution is obtained.

If only, the real power scheduling is changed, the load bus voltage magnitudes will remain fixed, because of the following facts :

i) The voltage magnitude variations at the load buses are not too sensitive to the real power changes.

ii) The reactive power equations depend weakly on the phase angles $[\theta]$ of the voltages

Hence, the load buses are eliminated by converting the loads into constant shunt admittances based on the converged voltage solution obtained, using the initial scheduling of real power generation and an equivalent system consisting of only P-V buses is obtained.

The problem is now reduced to :

Determine $[u_p]$ which minimizes $F_r([x], [u])$ subject to

i) load flow equations

$$[g_r([x], [u], [p])] = 0 \tag{4.15}$$

ii) limits on control variables $[u_p]$

where the subscript r refers to the reduced system consisting of only P-V buses.

Introducing the Lagrange multiplier vector $[\lambda_r]$, the constrained minimization problem is transformed into the minimization problem with respect to control vector $[u_p]$ of the unconstrained Lagrangian function L_r.

$$L_r = F_r([x], [u]) + [\lambda_r]^T [g_r([x], [u], [p])] \tag{4.16}$$

The necessary conditions for the minimum are

$$[L_{r\lambda r}] = [\frac{\partial L_r}{\partial \lambda_r}] = [g_r([x], [u], [p])] = [0] \tag{4.17}$$

$$[L_{rx}] = [\frac{\partial L_r}{\partial x}] = [\frac{\partial F_r}{\partial x}] + [\frac{\partial g_r}{\partial x}]^T [\lambda_r] = [0] \tag{4.18}$$

$$[L_{rup}] = [\frac{\partial L_r}{\partial u_p}] = [\frac{\partial F_r}{\partial u_p}] + [\frac{\partial g_r}{\partial u_p}]^T [\lambda_r] = [0] \tag{4.19}$$

The set of nonlinear equations (4.17 to 4.19) relating to an equivalent system consisting of only P-V buses is solved iteratively to obtain the optimal solutions.

4.4.3 NETR solution procedure

The main steps of the solution algorithm are as follows :

Step 1 : Start the iteration count for the gradient step k = 1

Step 2 : Read the system data. Assume a starting value for the control vector $[u_p]$ and for the unspecified voltage phase angles and magnitudes.

Step 3 : Check if $k > 1$; if it is go to step (5); otherwise continue.

Step 4 : Solve the load flow equation (4.7) by NETR load flow method, and obtain the converged solution. Store the matrices $[Y'_{GG}]$ (non-triangularized) and $[Y'_{LL}]$ (triangularized). Form $[\frac{\partial g_r}{\partial x}] = [\frac{\partial P}{\partial \theta_v}]$ and store its table of factors. Go to step (6).

Step 5 : Solve the load flow equations by NRM using the factors of $[\frac{\partial g_r}{\partial x}]$ available from step (4). Go to step (7).

Step 6 : Solve the equation (4.18) for $[\lambda_r]$ by a repeat solution using the factors of $[\frac{\partial g_r}{\partial x}]^T$ available from step (4). Go to step (8).

Step 7 : Solve the equation (4.18) for $[\lambda_r]$ by NRM using the factors of $[\frac{\partial g_r}{\partial x}]^T$ available from step (4).

Step 8 : At this point $([x], [u], [\lambda_r])$, compute the reduced gradient vector $[L_{rup}]$ from equation (4.19).

Step 9 : If $[L_{rup}]$ is sufficiently small, minimum has been reached and go to step (11). Otherwise, continue to the next step.

Step 10: Set the new values for u_{pi} as

$$u_{pi}^{k+1} = \begin{cases} u_{pi}^{max} \; ; & \text{if } u_{pi}^{k} + \Delta u_{pi}^{k} > u_{pi}^{max} \\ u_{pi}^{min} \; ; & \text{if } u_{pi}^{k} + \Delta u_{pi}^{k} < u_{pi}^{min} \\ (u_{pi}^{k} + \Delta u_{pi}^{k}) & \text{otherwise.} \end{cases}$$

where $\Delta u_{pi}^{k} = - \beta_i^k L_{rup}^k$

Advance the iteration count $k = k+1$ and return to step (3).

Step 11: Determine the load bus voltages from

$[Y'_{LL}][E_L] = -[Y_{LG}][E_G]$ (vide equation 2.53).

Now we have got the complete set of results.

4.5 NUMERICAL RESULTS ON TEST SYSTEMS AND COMPARISON

The adapted IEEE 14 bus, 30 bus and 57 bus test systems were used for obtaining OLF and economic dispatch solutions using the proposed NRM and NETR solution procedures respectively and the results are compiled in Tables 4.1 to 4.4. The different test system specifications including the generation cost are given in Appendix D. The optimal solutions obtained, using the original Dommel and Tinney's approach based on NM load flow are also included. A comparison of the results listed in Tables 4.1 to 4.4 reveals :

A. NRM Algorithm

1) The total computing time is less by about 50 to 60% as compared to by using NM.

2) The total number of gradient steps, load flow iterations and the optimum points reached are practically the same as compared to those obtained by using NM.

B. NETR Algorithm

1) The overall computer time is about 10 to 20% of that required by using NM.

2) The saving in computer time as obtained in (1) increases as the system size increases and as the number of P-V buses in the system decreases.

TABLE 4.1 OPTIMAL LOAD FLOW RESULTS USING NM, NRM AND NETR ALGORITHMS

IEEE 14 BUS SYSTEM

	Initial schedule	Optimal schedule		
		NM algorithm	NRM algorithm	NETR algorithm (only real power schedule)
real power generation (MW)				
P_{G2}	40.00	66.78	66.84	69,44
P_{G6}	00.00	40.80	40.50	36.42
bus voltage magnitude (p.u.)				
V_1	1.06	1.06	1.06	1.06
V_2	1.045	1.044	1.044	1.045
V_6	1.070	1.084	1.082	1.070
total power generation				
MW	272.38	268.07	268.13	268.48
MVAR	79.15	57.32	57.73	59.06
total generation cost $ per hr	1177.781	1135.703	1135.906	1136.764

TABLE 4.2 OPTIMAL LOAD FLOW RESULTS USING NM, NRM AND NETR ALGORITHMS

IEEE 30 BUS SYSTEM

	Initial schedule	Optimal schedule		
		NM algorithm	NRM algorithm	NETR algorithm (only real power schedule)
real power generation (MW)				
P_{G2}	80.00	50.23	50.22	52.19
P_{G5}	50.00	22.48	22.48	20.35
P_{G8}	20.00	20.41	20.20	14.74
P_{G11}	20.00	14.50	14.51	10.00
P_{G13}	20.00	14.03	14.03	12.00
bus voltage magnitude (p.u.)				
V_1	1.05	1.05	1.05	1.05
V_2	1.045	1.029	1.026	1.045
V_5	1.01	1.009	1.008	1.01
V_8	1.01	1.012	1.013	1.01
V_{11}	1.05	1.085	1.087	1.05
V_{13}	1.05	1.085	1.086	1.05
transformer tap setting				
t_{11}	0.978	1.012	1.010	0.978
t_{12}	0.969	0.940	0.940	0.969
t_{15}	0.932	1.009	1.009	0.932
t_{36}	0.968	0.952	0.980	0.968
total power generation				
MW	288.81	292.79	292.77	293.74
MVAR	108.96	122.10	119.36	127.38
total generation cost £ per hr	900.832	803.469	803.671	803.578

TABLE 4.3 OPTIMAL LOAD FLOW RESULTS USING NM, NRM AND NETR ALGORITHMS

IEEE 57 BUS SYSTEM

	Initial schedule	Optimal schedule		
		NM algorithm	NRM algorithm	NETR algorithm (only real power schedule
real power generation (MW)				
P_{G2}	40.00	100.00	100.00	100.00
P_{G3}	0.00	106.17	106.03	107.94
P_{G6}	0.00	100.18	100.13	99.66
P_{G8}	450.00	154.87	155.07	156.55
P_{G9}	0.00	300.00	300.00	300.00
P_{G12}	310.00	63.20	62.91	57.83
bus voltage magnitude (p.u.)				
V_1	1.04	1.036	1.036	1.04
V_2	1.01	1.042	1.041	1.01
V_3	0.985	1.032	1.028	0.985
V_6	0.980	1.014	1.011	0.980
V_8	1.005	1.000	1.000	1.005
V_9	0.980	1.012	1.006	0.980
V_{12}	1.015	0.994	0.986	1.015
total power generation				
MW	1280.92	1289.29	1289.42	1291.55
MVAR	302.43	323.97	325.88	316.68
total generation cost £ per hr	8443.422	4775.650	4776.210	4786.206

TABLE 4.4 COMPUTATIONAL COMPARISON BETWEEN NM, NRM AND NETR ALGORITHMS FOR OPTIMAL LOAD FLOW

(IEEE 14 BUS, 30 BUS AND 57 BUS TEST SYSTEMS)

Method	IEEE 14 bus system			IEEE 30 bus system			IEEE 57 bus system		
	Total No. of gradient steps	Total No. of load flow iterations	Relative computer time in % on DEC 1090 system	Total No. of gradient steps	Total No. of load flow iterations	Relative computer time in % on DEC 1090 system	Total No. of gradient steps	Total No. of load flow iterations	Relative computer time in % on DEC 1090 system
NM algorithm	16	26	100	13	20	100	17	31	100
NRM algorithm	16	26	84	13	21	51	17	33	41
NETR algorithm	12	16	20	11	16	8	15	30	4

3) The total number of gradient steps, load flow iterations, and the optimum values for real power generation are slightly different from those obtained by using NM, while the cost of generation of the optimum point is in close agreement.

4) The assumption that the different real power schedules do not change the load bus voltages very much is quite valid.

4.6 CONCLUSION

In this chapter, we have presented new solution procedures for OLF and economic dispatch calculations based on NRM and NETR load flow techniques respectively. It is reported in reference [72] that the method using FDLP gives an overall advantage in speed of 2 to 1 over the method of Dommel and Tinney. Since, the proposed NRM algorithm gives an overall savings in computing times of more than 50% compared to the method of Dommel and Tinney, it is competitive to the method using FDLP in terms of speed, while the Jacobian is available for further applications. The proposed NETR algorithm for economic dispatch requires about 10 to 20% of the overall computer time compared to the method of Dommel and Tinney. We may thus conclude from above, that this algorithm is atleast twice as fast as the one due to FDLP [72], and is thus ideally suited for real-time applications. The effectiveness of the proposed techniques is demonstrated on the adapted IEEE 14 bus, 30 bus and 57 bus test systems.

CHAPTER V

TWO LEVEL SOLUTIONS FOR LARGE SCALE POWER SYSTEMS

5.1 INTRODUCTION

The large scale nature of the modern power systems requires the application of sparse matrix and/or decomposition techniques. A number of decomposition techniques are available in the literature which can be implemented in single [11,27,39] or multicomputer [11,85-87,96,97] configurations. In the last few years, there has been a considerable interest in hierarchical control methods in which the overall problem is split into a set of smaller subproblems coordinated by a central agency. Brameller and Lo [92] proposed a diakoptical optimization procedure in Y_{BUS} formulation using the method of Dommel and Tinney [65]. Although it is reported that the method is suitable for multicomputer configuration, test results are not given in this reference. Sasson [90] presented a decomposition technique to solve the load flow problem using nonlinear programming method. This method overcomes the convergence difficulties encountered in the application of the nonlinear programming load flow method to large scale systems. Happ proposed a d.c. load flow [87] and real power dispatch [86] procedure in the multiarea case. This method of real power dispatch utilizes

the well known B-coefficients. Narita and Hammam [98] and Kobayashi et al [93] discussed the voltage and reactive power control for real-time applications amenable to multicomputer computation. More recently, Irving et al [107] made a comparative study of the application of different linear programming methods for on-line real power dispatch using the hierarchical control theory. Bielli et al [108] proposed a two level technique for the economic real power dispatch based on the hierarchical approach. These methods by Happ, Irving and Bielli do not take care of the limits on the reactive power and bus voltages.

The main objective of this chapter is to present a new two level optimal load flow procedure using the nonlinear programming method of Dommel and Tinney [65]. It optimizes both the real and reactive power using the adjustable real power generations, voltage magnitude of generators and transformer tap ratios as control variables. Before describing the proposed optimal load flow method, the two level NM, NRM and FDLP load flow solution algorithms are presented. The proposed two level technique combines the advantages of both decomposition and sparsity and is suitable for multicomputer configuration. The information relating to only the cut buses is transmitted between the two levels. The convergence characteristics depend on the value of the acceleration factor used and the number of areas into which the original system is decomposed.

To implement the two level technique, a large scale power system is torn into several subsystems or areas by removing the connecting lines. Each area has its own dispatch computer, and in addition, there is a pool dispatch computer. There is no direct communication between the areas. The decoupling of different areas is achieved by introducing pseudo variables. In the first level the area solutions are obtained. The second level (pool dispatch computer) coordinates the areas via pseudo variables. This process is iterated until the specified convergence criteria is satisfied. The proposed two level algorithms for the load flow and optimal load flow problems have been tested on the IEEE 30 bus and 57 bus systems, decomposed into 2 or 3 areas.

5.2 LOAD FLOW

5.2.1 Development of multiarea load flow equations

The large scale power system is torn into N areas by removing the cut lines. The following assumptions are made for the system tearing.

1) No mutual coupling should exist between the lines belonging to the different areas.
2) Each area is individually connected.
3) A common bus (usually the ground) is available for all the areas.

The general guide for the system tearing is as follows :

1) Separation of the networks of different utilities, identifiable power pools etc.

2) Employment of the various proposed network tearing algorithms [91,95,102]

For the ith area, we define

$[V^i]$ = bus voltage magnitude vector

$[\theta^i]$ = bus voltage angle vector

$[P_G^i]$ = real power generation vector

$[Q_G^i]$ = reactive power generation vector

$[P_L^i]$ = real power load vector

$[Q_L^i]$ = reactive power load vector

$[x^i]$ = state vector or dependent vector

$[u^i]$ = control vector or independent vector

$[p^i]$ = parameter vector

(vide Chapter IV Section 4.2)

n_p^i = number of generators

$[P_{in}^i]$ = real power injection vector due to the cut lines

$[Q_{in}^i]$ = reactive power injection vector due to the cut lines

$$[W_c] = \begin{bmatrix} [P_c] \\ \hline [Q_c] \end{bmatrix}$$ = cut line real power and reactive power flow vector

(a) Cut line flow equations

The real and reactive cut line power flows are treated as additional problem variables. They can be written as a function of bus voltages and cut line parameters. The real and reactive power flows in the ℓth cut line interconnecting the

pth bus in the area i and qth bus in the area j are

$$P^{\ell}_{c(p,q)} = -V^i_p V^j_q (\hat{g}_{\ell} \cos(\theta^i_p - \theta^j_q) + b_{\ell} \sin(\theta^i_p - \theta^j_q)) + V^i_p V^i_p \hat{g}_{\ell} + V^i_p V^i_p \frac{\hat{g}'_{\ell}}{2} \qquad (5.1)$$

$$Q^{\ell}_{c(p,q)} = -V^i_p V^j_q (\hat{g}_{\ell} \sin(\theta^i_p - \theta^j_q) - b_{\ell} \cos(\theta^i_p - \theta^j_q)) - V^i_p V^i_p b_{\ell} - V^i_p V^i_p \frac{b'_{\ell}}{2} \qquad (5.2)$$

where

$y = \hat{g}_{\ell} + j\, b_{\ell}$ = admittance of the ℓth cut line

$y' = \hat{g}'_{\ell} + j\, b'_{\ell}$ = total line charging admittance

(b) Multiarea load flow equations

The real and reactive power injections due to the cut lines in the area i are given by

$$[P^i_{in}] = [C^i_p]\ [P_c] \qquad (5.3)$$

$$[Q^i_{in}] = [C^i_q]\ [Q_c] \qquad (5.4)$$

where $[C^i]$ = bus connection matrix which gives the connection of cut lines to the buses in area i.

The element C_{aj} (row a; column j) is given as

C_{aj} = 1, if the cut line j is connected to the bus a

= 0, if the cut line j is not connected to the bus a

The matrices $[C^i_p]$ and $[C^i_q]$ are the same only if there are no P-V buses present in the area i. Otherwise $[C^i_q]$ is obtained

from $[C_p^i]$ by deleting the rows corresponding to the P-V buses.

Then, the real and reactive load flow equations for the area i will be

$$[P_G^i] - [P_L^i] - [P^i(\theta^i, V^i)] - [C_p^i][P_c] = 0 \qquad (5.5)$$

$$[Q_G^i] - [Q_L^i] - [Q^i(\theta^i, V^i)] - [C_q^i][Q_c] = 0 \qquad (5.6)$$

In concise form, the multiarea load flow equations can be written as

$$[g^i([x^i], [u]^i], [p^i])] - [C^i][W_c] = 0 \qquad (5.7)$$

The cut line flow equations are given by

$$[g_c([x^1], [u^1], [x^2], [u^2] \ldots [x^N], [u^N])] - [W_c] = 0 \qquad (5.8)$$

Combining (5.7) and (5.8), we get

$$[g^i([x^i], [u^i], [p^i])] - [C^i][g_c([x^1], [u^1], [x^2], [u^2] \ldots$$
$$[x^i], [u^i], [x^N], [u^N])] = 0; \; i = 1,2, \ldots N \qquad (5.9)$$

As such, equation (5.9) cannot be solved independently, because of the coupling terms. We introduce ~~pseudo~~ variables $[\sigma]$ as per the following relationship to uncouple the terms in equation (5.9)

$$[\sigma_x^i] = [x^i] \qquad (5.10)$$

$$[\sigma_u^i] = [u^i]; \; i = 1,2, \ldots N \qquad (5.11)$$

Then, equation (5.9) reduces to

$$[g^i([x^i], [u^i], [p^i])] - [C^i][g_c([\sigma_x^1], [\sigma_u^1], [\sigma_x^2], [\sigma_u^2], \ldots$$

$$[x^i], [u^i], \ldots [\sigma_x^N], [\sigma_u^N])] \quad ; \quad i = 1,2, \ldots N \qquad (5.12)$$

(c) First level

The pseudo variables $[\sigma_x^j], [\sigma_u^j]$ $(j = 1,2, \ldots N, j \neq i)$ are assumed to be known as far as the area i is concerned. Then, the load flow equations (5.12) are solved independently for each area.

(d) Second Level

The pseudo variables $[\sigma_x^j]$, $[\sigma_u^j]$, $(j = 1,2, \ldots N)$ are determined using equations (5.10) and (5.11).

(e) Acceleration Method

To achieve better convergence for the iterative process, an acceleration method - Successive Over Relaxation (SOR) can be used in the first level or in the second level. However, the acceleration at the first level is found to decrease the number of iterations for convergence.

Acceleration at the first level :

At every calculation of $[x^i]$, a correction is applied in the following manner

$$[\Delta x^i]^{k+1} = \alpha^i ([x^i]^{k+1} - [x^i]^k) \qquad (5.13)$$

where α^i is the acceleration factor for area i, with the value ranging between 1 and 2, and k is the iteration number. Then,

$$[x^i]^{k+1} = [x^i]^k + [\Delta x^i]^{k+1} \quad ; \; i = 1,2, \ldots N \qquad (5.14)$$

Fig. (5.1) shows the transfer of information between the first and second levels for the load flow solution.

5.2.2 Solution of multiarea load flow equations

(a) Newton-Raphson Technique

Linearizing the equations given by (5.12) using Taylor series expansion and simplifying we get,

$$\begin{bmatrix} [\Delta P^i] \\ \hline [\Delta Q^i] \end{bmatrix} = [\hat{J}^i] \begin{bmatrix} [\Delta \theta^i] \\ \hline [\frac{\Delta V^i}{V^i}] \end{bmatrix} \qquad (5.15)$$

$$i=1,2,\ldots N$$

where

$$[\hat{J}^i] = \left[\begin{array}{c|c} [\hat{J}^i_1] = [\frac{\partial (P+P_{in})^i}{\partial \theta}] & [\hat{J}^i_2] = [\frac{\partial (P+P_{in})^i}{\partial V}] \\ \hline [\hat{J}^i_3] = [-\frac{\partial (Q+Q_{in})^i}{\partial \theta}] & [\hat{J}^i_4] = [\frac{\partial (Q+Q_{in})^i}{\partial V}] \end{array}\right]$$

$[\Delta P^i]$ = real power mismatch vector

$[\Delta Q^i]$ = reactive power mismatch vector

$[\Delta \theta^i]$ = voltage phase angle increment vector

$[\Delta V^i]$ = bus voltage magnitude increment vector

$[\hat{J}^i_j]_{j=1 \text{ to } 4}$ = submatrices of the Jacobian

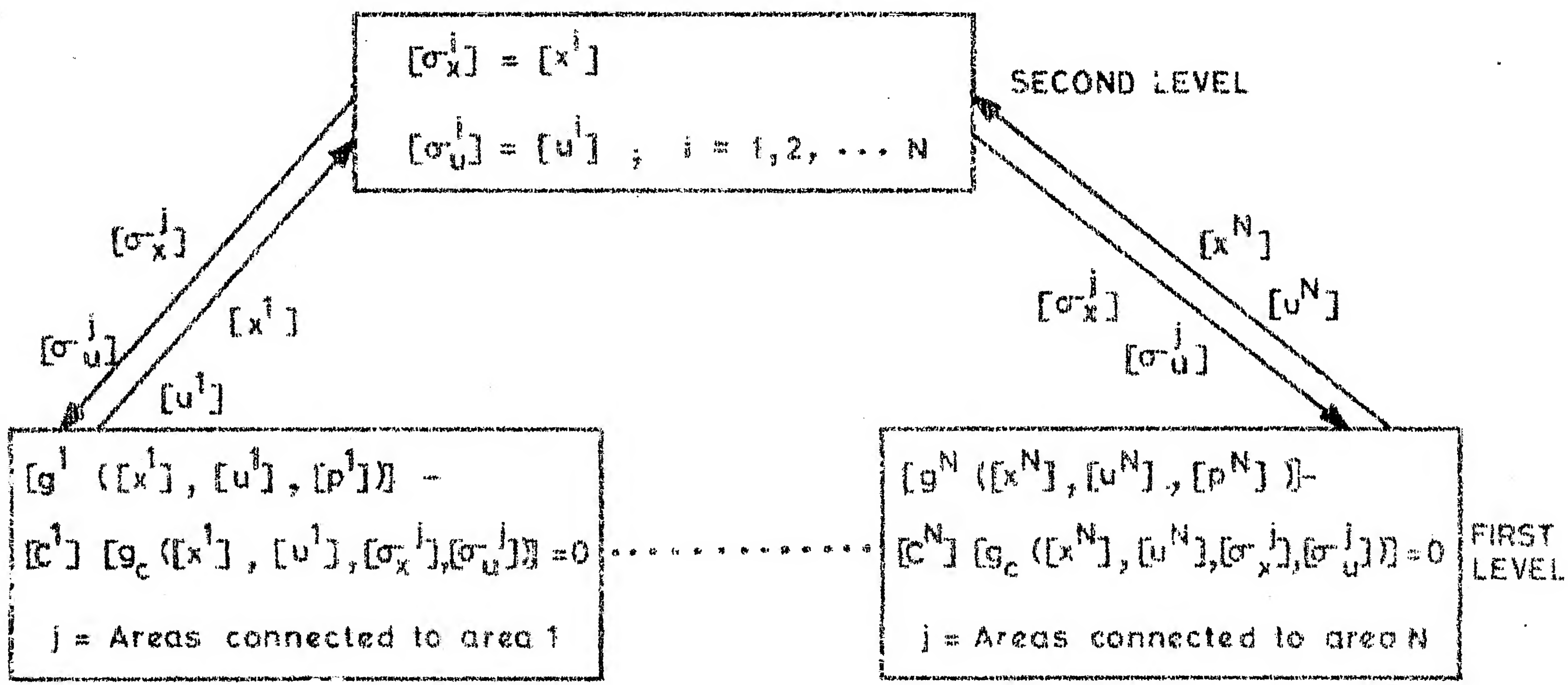


FIG. 5.1 TWO LEVEL STRUCTURE OF THE LOAD FLOW SOLUTION.

(b) Newton-Richardson Technique

Let $[\hat{J}^{(0)^i}]$ = Jacobian matrix evaluated using the initial estimates.

Then applying Newton-Richardson technique (vide Chapter II, Section 2.5.1) for each subsystem, we get the final converged value of $[\Delta x^i]^{(k)}$ at the kth major step as

$$[\Delta x^i]^{(k)} = [\delta x^i]_0^{(k)} + [\delta x^i]_1^{(k)} + \ldots \tag{5.16}$$

$$i = 1, 2, \ldots N$$

where

$$[\delta x^i]_0^{(k)} = [\hat{J}^{(0)^i}]^{-1} \left\{ \begin{bmatrix} \Delta P^i \\ \hline \Delta Q^i \end{bmatrix} \right\}$$

$$[\delta x^i]_1^{(k)} = [\hat{J}^{(0)^i}]^{-1} \left\{ \begin{bmatrix} \Delta P^i \\ \hline \Delta Q^i \end{bmatrix} - [\hat{J}^{(i)}]^{(k)} \quad [\delta x^i]_0^{(k)} \right\}$$

and so on.

(c) Fast Decoupled Technique

The coupling matrices $[\hat{J}_2^i]$ and $[\hat{J}_3^i]$ are neglected in equation (5.15) by application of the decoupling principle. The resulting equations are further modified by incorporating the suggestions proposed in the reference [29] to yield,

$$\left[\frac{\Delta P^i}{V}\right] = [B_p'^i] \quad [\Delta\theta^i] \tag{5.17}$$

$$\left[\frac{\Delta Q^i}{V}\right] = [B_q''^i] \; [\Delta V^i] \quad ; \; i = 1, 2, \ldots N \tag{5.18}$$

where $[B'^{i}_{p}] = [B'^{i}] + [B'^{i}_{in}]$

$[B''^{i}_{q}] = [B''^{i}] + [B''^{i}_{in}]$

$[B'^{i}_{in}]$ and $[B''^{i}_{in}]$ are the diagonal matrices with elements composed of only the cut line susceptances. Since $[B'^{i}]$ and $[B''^{i}]$ contain only the branch susceptances of the area i, the matrices $[B'^{i}_{p}]$ and $[B''^{i}_{p}]$ are real, sparse and constant and hence they need to be triangularized only once, at the start of the iterative process.

5.3 OPTIMAL LOAD FLOW

5.3.1 Multiarea power system optimization problem

The multiarea optimal load flow problem can be stated as follows :

Minimize the scalar objective function F of the system variables

$$F = F^{1}([x^{1}], [u^{1}]) + F^{2}([x^{2}], [u^{2}]) + \ldots F^{N}([x^{N}],[u^{N}]) \tag{5.19}$$

subject to the following equality and inequality constraints.

a) Equality constraints

(1) Area load flow equations

$$[g^{i}([x^{i}], [u^{i}], [p^{i}])] - [W^{i}_{c}] = 0; \; i = 1,2, \ldots N \tag{5.20}$$

(2) Area equivalent cut line injection equations

$$[g_c^i([x^1], [u^1], [x^2], [u^2] \ldots [x^N], [u^N])] - [W_c^i] = 0$$

$$i = 1, 2, \ldots N \qquad (5.21)$$

where

$$[W_c^i] = [C^i][W_c]$$

and

$$[g_c^i([x^1], [u^1], [x^2], [u^2] \ldots [x^N], [u^N])] =$$

$$[C^i][g_c([x^1], [u^1], [x^2], [u^2] \ldots [x^N], [u^N])]$$

(b) Inequality constraints

These are the lower and upper limits on real and reactive power generation, voltage magnitude, transformer tap positions, slack bus power and line flows. In compact form, these are represented for the ith area as

$$u^i_{j\,min} \leqslant u^i_j \leqslant u^i_{j\,max} \qquad (5.22)$$

$$h^i_{j\,min} \leqslant h^i_j \leqslant h^i_{j\,max} \qquad (5.23)$$

The objective function is the overall cost of production and it takes the form for the ith area as

$$F^i([x^i], [u^i]) = \sum_{j=1}^{n_p^i} (a^i_{oj} + b^i_{oj} P^i_{Gj} + c^i_{oj} (P^i_{Gj})^2) \qquad (5.24)$$

Using the classical optimization method of Lagrange multipliers

[65], the minimum of objective function F subject to the equality constraints is found by minimizing the augmented objective function known as the Lagrangian function.

5.3.2 The Lagrangian function

The Lagrangian function is formed as

$$L_o = \sum_{i=1}^{N} F^i([x^i], [u^i]) + \sum_{i=1}^{N} [\lambda^i]^T \{ [g^i([x^i], [u^i], [p^i])] - [W_c^i] \} + \sum_{i=1}^{N} [\lambda_c^i]^T \{ [g_c^i([x^1], [u^1], [x^2], [u^2] \ldots [x^N], [u^N])] - [W_c^i] \} \tag{5.25}$$

where

$[\lambda^i]$ = vector of Lagrange multipliers for the ith area load flow equations.

$[\lambda_c^i]$ = vector of Lagrange multipliers for the area equivalent cut line injection equations.

5.3.3 Two level formulation

The Lagrangian function is decomposed by introducing the additional variables called as pseudo variables $[\sigma]$ as given by (5.10) and (5.11). This allows each area to be decoupled and hence solved independently. These equations result in the additional equality constraints represented by

$$[\sigma_x^i] - [x^i] = 0 \tag{5.26}$$

and

$$[\sigma_u^i] - [u^i] = 0 \; ; \quad i = 1,2, \ldots N \tag{5.27}$$

With the above equality constraints, the Lagrangian function L_o is modified as

$$L = L_o + \sum_{i=1}^{N} [\lambda_{\sigma_x}^{i}]^T \{[\sigma_x^i] - [x^i]\} + \sum_{i=1}^{N} [\lambda_{\sigma_u}^{i}]^T \{[\sigma_u^i] - [u^i]\} \tag{5.28}$$

where $[\lambda_{\sigma_x}^{i}]$ and $[\lambda_{\sigma_u}^{i}]$ are the Lagrange multiplier vectors for the equality constraints introduced by the pseudo variables.

The total Lagrangian is readily split into N independent sub-Lagrangians by considering $[\sigma_x^j]$ and $[\sigma_u^j]$ as constant except for the area i as indicated below.

$$L = \sum_{i=1}^{N} L_i \tag{5.29}$$

where

$$\begin{aligned} L_i = {} & F^i([x^i], [u^i]) + [\lambda^i]^T \{[g^i([x^i], [u^i], [p^i])] - [W_c^i]\} \\ & + [\lambda_c^i]^T \{[g_c^i([\sigma_x^1], [\sigma_u^1], [\sigma_x^2], [\sigma_u^2] \ldots [x^i], [u^i] \ldots \\ & [\sigma_x^N], [\sigma_u^N])] - [W_c^i]\} - [\lambda_{\sigma_x}^{i}]^T [x^i] - [\lambda_{\sigma_u}^{i}]^T [u^i] \\ & + \sum_{\substack{j=1 \\ j \neq i}}^{N} [\lambda_{\sigma_x}^{i}]^T [\sigma_x^j] + \sum_{\substack{j=1 \\ j \neq i}}^{N} [\lambda_{\sigma_u}^{i}]^T [\sigma_u^j] \end{aligned}$$

5.3.4 Optimality criterian

(a) First level

There are N areas in the first level of the hierarchical structure with independent Lagrangians. Necessary conditions for stationarity for L_1, L_2, ... L_N are

$$[L_x^i] = [\frac{\partial L_i}{\partial x^i}] = [\frac{\partial F_r^i}{\partial x^i}] + [\frac{\partial g^i}{\partial x^i}]^T [\lambda^i] + [\frac{\partial g_c^i}{\partial x^i}]^T [\lambda_c^i] - [\lambda_{\sigma_x}^i] = 0 \qquad (5.30)$$

$$[L_u^i] = [\frac{\partial L_i}{\partial u^i}] = [\frac{\partial F^i}{\partial u^i}] + [\frac{\partial g^i}{\partial u^i}]^T [\lambda^i] + [\frac{\partial g_c^i}{\partial u^i}] [\lambda_c^i] - [\lambda_{\sigma u}^i] = 0 \qquad (5.31)$$

$$[L_\lambda^i] = [\frac{\partial L_i}{\partial \lambda^i}] = [g^i([x^i], [u^i], [p^i])] - [W_c^i] = 0 \qquad (5.32)$$

$$[L_{W_c}^i] = [\frac{\partial L_i}{\partial W_c^i}] = [\lambda^i] - [\lambda_c^i] = 0 \qquad (5.33)$$

$$[L_{\lambda_c}^i] = [\frac{\partial L_i}{\partial \lambda_c^i}] = [g_c^i([x^i], [u^i], [\sigma_x^j], [\sigma_u^j])] - [W_c^i] = 0 \qquad (5.34)$$

for i = 1,2, ..., N; j = 1,2, ... N and $j \neq i$

Substituting for $[\lambda_c^i]$ and $[W_c^i]$ obtained from (5.33) and (5.34) in equations (5.30 to 5.32), we get

$$[L_x^i] = [\frac{\partial F^i}{\partial x^i}] + [\frac{\partial (g^i+g_c^i)}{\partial x^i}]^T [\lambda^i] - [\lambda_{\sigma_x}^i] = 0 \qquad (5.35)$$

$$[L_u^i] = [\frac{\partial F^i}{\partial u^i}] + [\frac{\partial (g^i+g_c^i)}{\partial u^i}]^T [\lambda^i] - [\lambda_{\sigma_u}^i] = 0 \qquad (5.36)$$

$$[L_\lambda^i] = [g^i([x^i], [u^i], [p^i])] - [g_c^i([x^i], [u^i], [\sigma_x^j], [\sigma_u^j])] = 0 \tag{5.37}$$

for $i = 1,2, \ldots N$; $j = 1,2, \ldots N$ and $j \neq i$

For any given values of $[\lambda_{\sigma_x}^{\ i}]$, $[\lambda_{\sigma_u}^{\ i}]$, $[\sigma_x^j]$ and $[\sigma_u^j]$ determined at the 2nd level, equations (5.35 to 5.37) give the corresponding optimal decisions $[x^i]$, $[u^i]$, $[\lambda^i]$ and hence $[\lambda_c^i]$ at the first level.

(b) Second level

The total Lagrangian system equation (5.29) is optimized at the second level. Necessary conditions for stationarity for L are

$$\left[\frac{\partial L}{\partial \lambda_{\sigma_x}^{\ i}}\right] = [\sigma_x^i] - [x^i] = 0 \tag{5.38}$$

$$\left[\frac{\partial L}{\partial \lambda_{\sigma_u}^{\ i}}\right] = [\sigma_u^i] - [u^i] = 0 \tag{5.39}$$

$$\left[\frac{\partial L}{\partial \sigma_x^i}\right] = [\lambda_{\sigma_x}^{\ i}] + \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[\frac{\partial g_c^j}{\partial \sigma_x^i}\right]^T [\lambda_c^j] = 0 \tag{5.40}$$

$$\left[\frac{\partial L}{\partial \sigma_u^i}\right] = [\lambda_{\sigma_u}^i] + \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[\frac{\partial g_c^j}{\partial \sigma_u^i}\right]^T [\lambda_c^j] = 0 \tag{5.41}$$

for $i = 1,2, \ldots N$.

For any given values of $[x^i]$, $[u^i]$ and $[\lambda_c^i]$ determined at the first level, equations (5.38 to 5.41) yield the corresponding optimal decisions $[\sigma_x^i]$, $[\sigma_u^i]$, $[\lambda_{\sigma_x}^i]$ and $[\lambda_{\sigma_u}^i]$ at the second level.

5.3.5 Solution technique

The results summarized by equations (5.35 to 5.41) are used to solve the two level optimization iteratively in three major steps as indicated below.

Step (1) : Calculation of state vector $[x]$

Assume a starting value for the control vector $[u]$. Then, the state vector $[x]$ is obtained by solving the multi-area load flow equations represented by (5.37) in the first level and the equations (5.38) and (5.39) in the second level iteratively in exactly the same manner as described in Section 5.2.

Step (2) : Calculation of Lagrange multiplier vector $[\lambda]$

From (5.35) and (5.40) we get

$$[\lambda^i] = - \left[\frac{\partial (g^i + g_c^i)}{\partial x^i} \right]^{T^{-1}} \left\{ \left[\frac{\partial F^i}{\partial x^i} \right] - [\lambda_{\sigma_x}^i] \right\} \qquad (5.42)$$

... First level

$$[\lambda_{\sigma_x}^i] = - \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[\frac{\partial g_c^j}{\partial \sigma_x^i} \right]^T [\lambda^j] \qquad (5.43)$$

... Second level

for i = 1,2, ... N

For the converged value of $[x]$ available from step (1), equations (5.42) and (5.43) are solved iteratively to obtain $[\lambda]$. To speed up the convergence rate, an acceleration method (SOR) is used in the first level.

Step (3) : Calculation of control vector $[u]$

For the set of values $[x]$ and $[\lambda]$ available from steps (1) and (2), $[\lambda^i_{\sigma u}]$ is calculated at the second level using equation (5.41). Then, in the first level $[L^i_u]$ is calculated using equation (5.36). If $[L^i_u]$ is sufficiently small, indicating that no further improvement in the objective function is possible through the control of $[u^i]$ and therefore the minimum is reached. Otherwise, adjust the control vector in the negative gradient direction using the formula

$$[u^i]^{k+1} = [u^i]^k + [\Delta u^i]^k \tag{5.44}$$

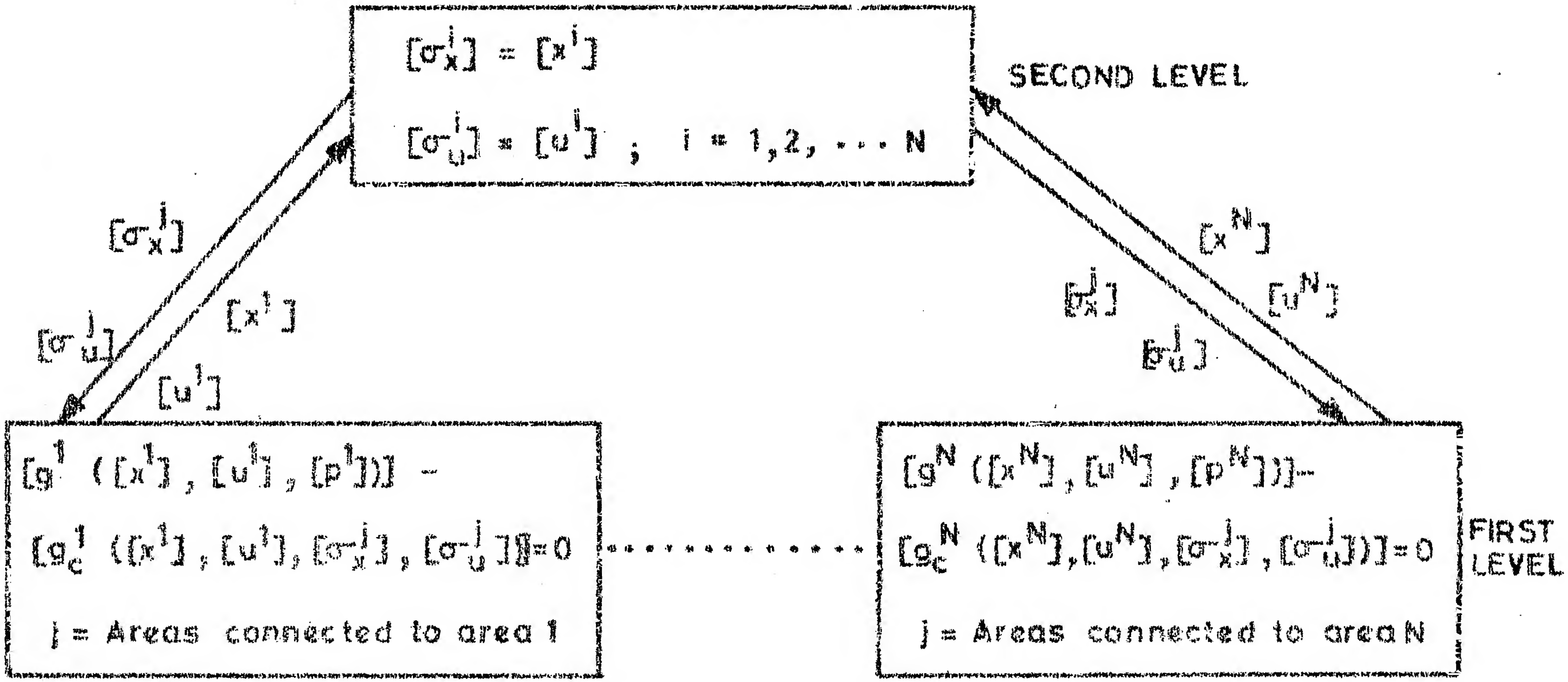
where

$$[\Delta u^i]^k = - \beta^{i\,k} [L^i_u]^k \tag{5.45}$$

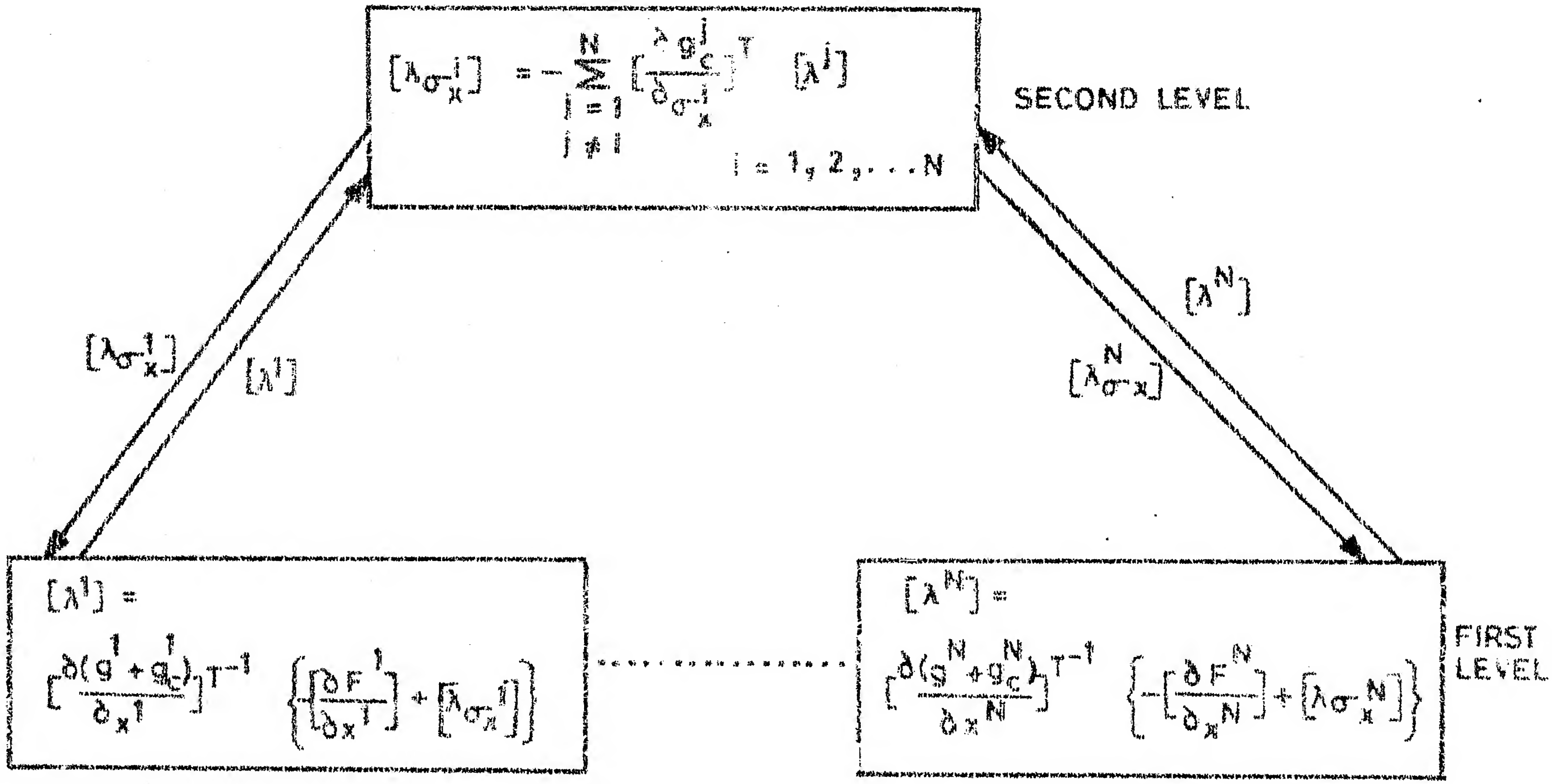
$$i = 1, 2, \ldots N$$

and return to step (1). β is a scalar and is known as the step length. Its value can be chosen in a similar manner as indicated in the preceding chapter, Section 4.3.3.

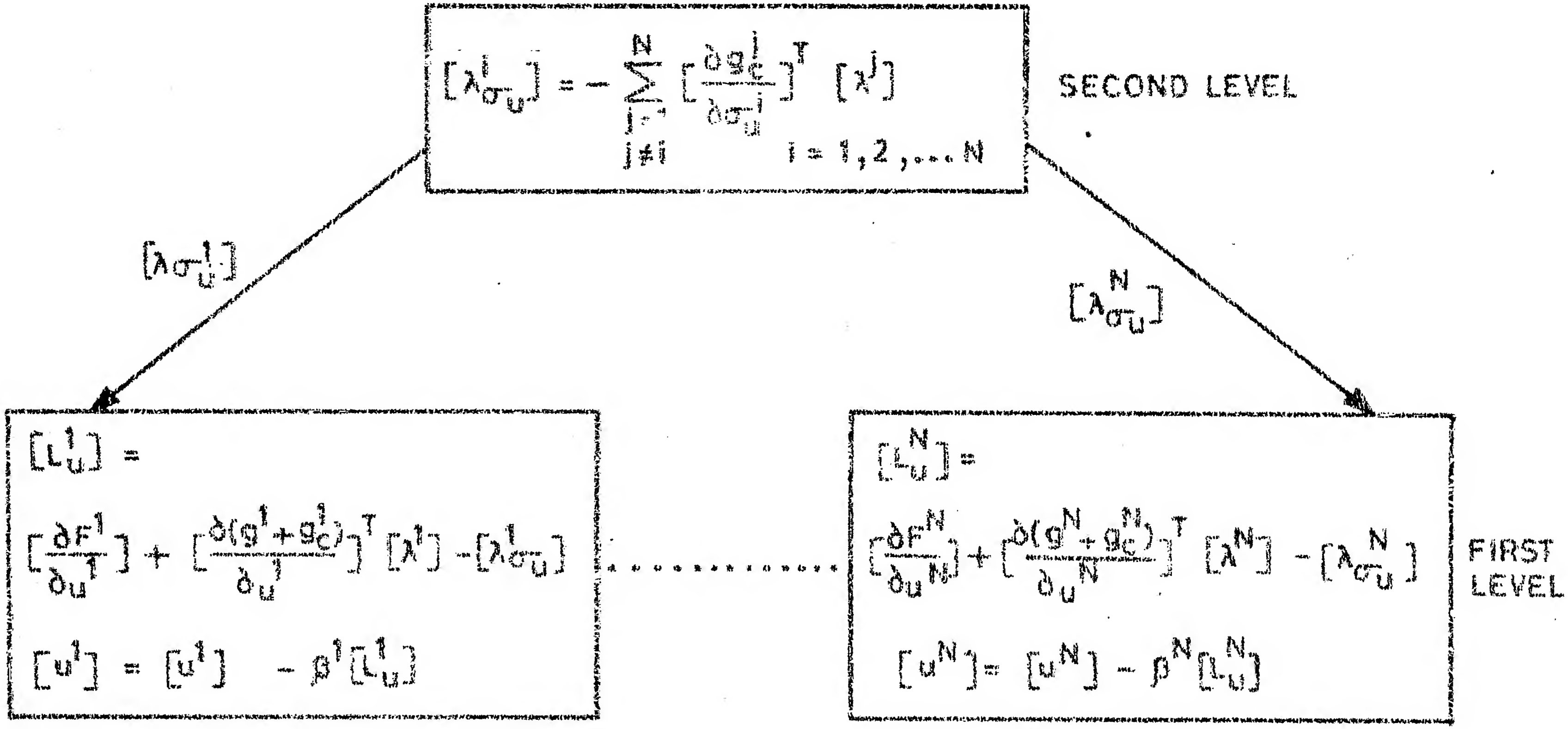
Fig. (5.2a-c) depicts the transfer of information between the first and second levels at the three major steps of the optimization.



(a) Calculation of [x]



(b) Calculation of $[\lambda]$



(c) Calculation of [u]

FIG.5.2 TWO LEVEL STRUCTURE OF THE OPTIMIZATION METHOD.

5.3.6 Inequality constraints

The inequality constraints encountered in the optimization process are given as :

a) Parameter inequality constraints

These are the constraints applied to individual control variables namely

$$[u^i_{min}] \leqslant [u^i] \leqslant [u^i_{max}] \quad ; \quad i = 1,2, \ldots N$$

As indicated in Chapter IV, Section 4.3.4, in the event that the correction Δu^i_j found from eqn. (5.45) causes the new value of the jth control variable in the area i, i.e. $u^{i(k+1)}_j$, to exceed one of its limits, the solution algorithm sets u^i_j to the corresponding limit.

$$u^{i(k+1)}_j = \begin{cases} u^i_{j\ max}; & \text{if}(u^{i(k)}_j + \Delta u^{i(k)}_j) > u^i_{j\ max} \\ u^i_{j\ min}; & \text{if}(u^{i(k)}_j + \Delta u^{i(k)}_j) < u^i_{j\ min} \\ u^{i(k)}_j + \Delta u^{i(k)}_j; & \text{otherwise} \end{cases}$$

b) Functional inequality constraints

The inequality constraints not involving the control variables are taken into account by the penalty function method as indicated in Chapter IV, Section 4.3.4. The objective function is augmented for the ith area as

$$F^i([x^i], [u^i]) = F^i_o([x^i], [u^i]) + \sum_{j \in m^i} R^i_j$$

$$i = 1,2, \ldots N$$

where F_o^i is the original objective function and $\hat{m}$ is the set of all the violated constraints in the area i and R_j^i is the penalty function for each of the violated functional constraints in the area i

$$R_j^i = \gamma_j^i (h_j^i - h_{j\,max}^i)^2 \quad \text{if} \quad h_j^i > h_{j\,max}^i$$

$$= \gamma_j^i (h_{j\,min}^i - h_j^i)^2 \quad \text{if} \quad h_j^i < h_{j\,min}^i$$

where γ^i is the penalty factor and h^i is the compact representation for the functional inequality constraints in the area i.

5.4 NUMERICAL RESULTS ON TEST SYSTEMS AND COMPARISON

The proposed two level computational method was applied to the adapted IEEE 30 bus and 57 bus test systems shown in Figures 5.3 and 5.4 respectively. The system specifications are given in Appendix D. These systems were decomposed into two as well as three areas. The load flow results obtained by solving the multi-area load flow equations using NM, NRM and FDLP techniques are shown in Tables 5.1 and 5.2. Tables 5.1 and 5.2 show the total number of iterations, the relative CPU time in percentage and the optimum acceleration factor for the different systems studied. Table 5.3 gives the effect of acceleration factor on the number of load flow iterations needed for the convergence of IEEE 57 bus system. For comparison, the results obtained based on the computation without decomposition are also given.

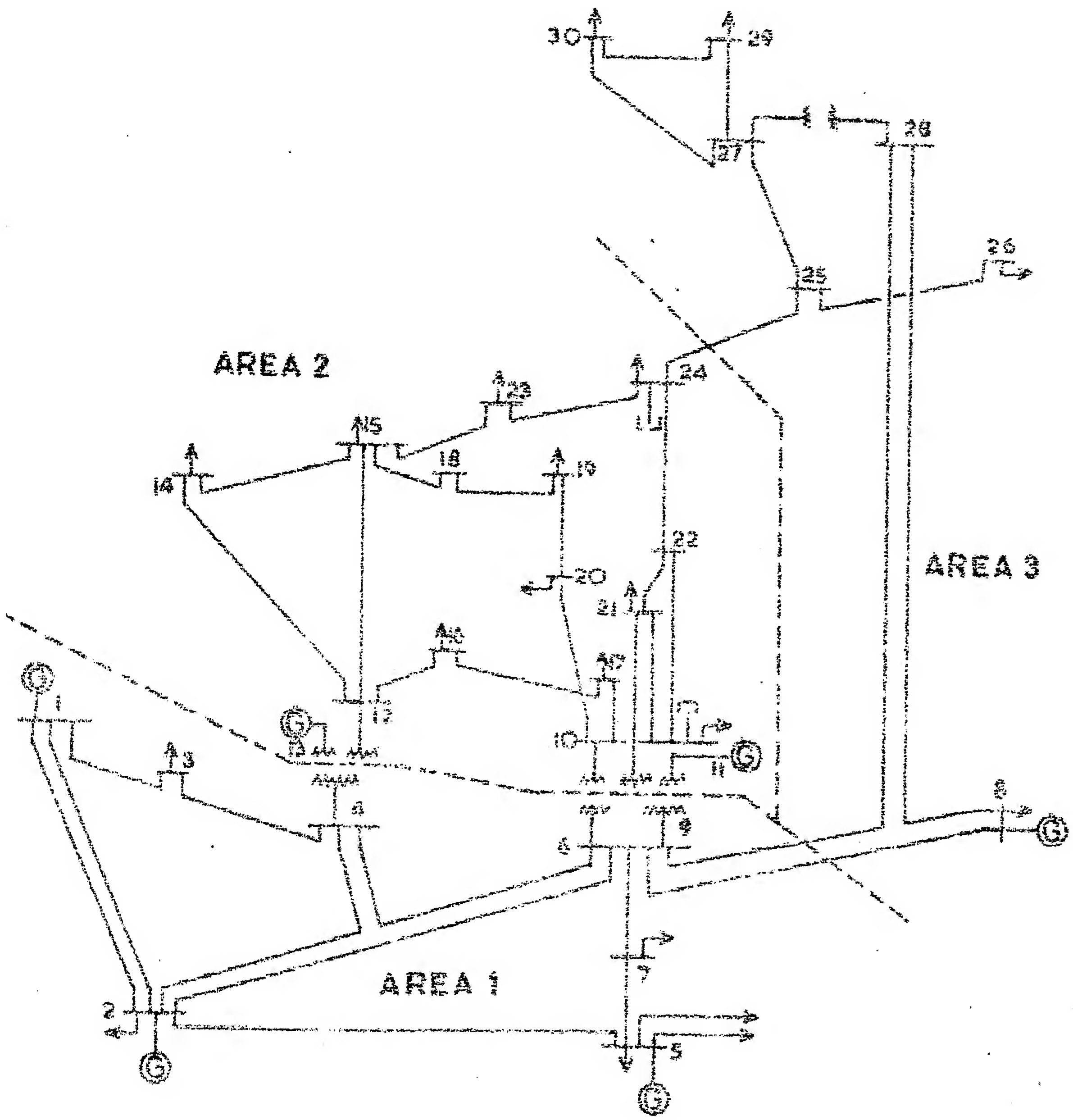


FIG. 5.3 IEEE 30-BUS SYSTEM DECOMPOSED INTO 3 AREAS.

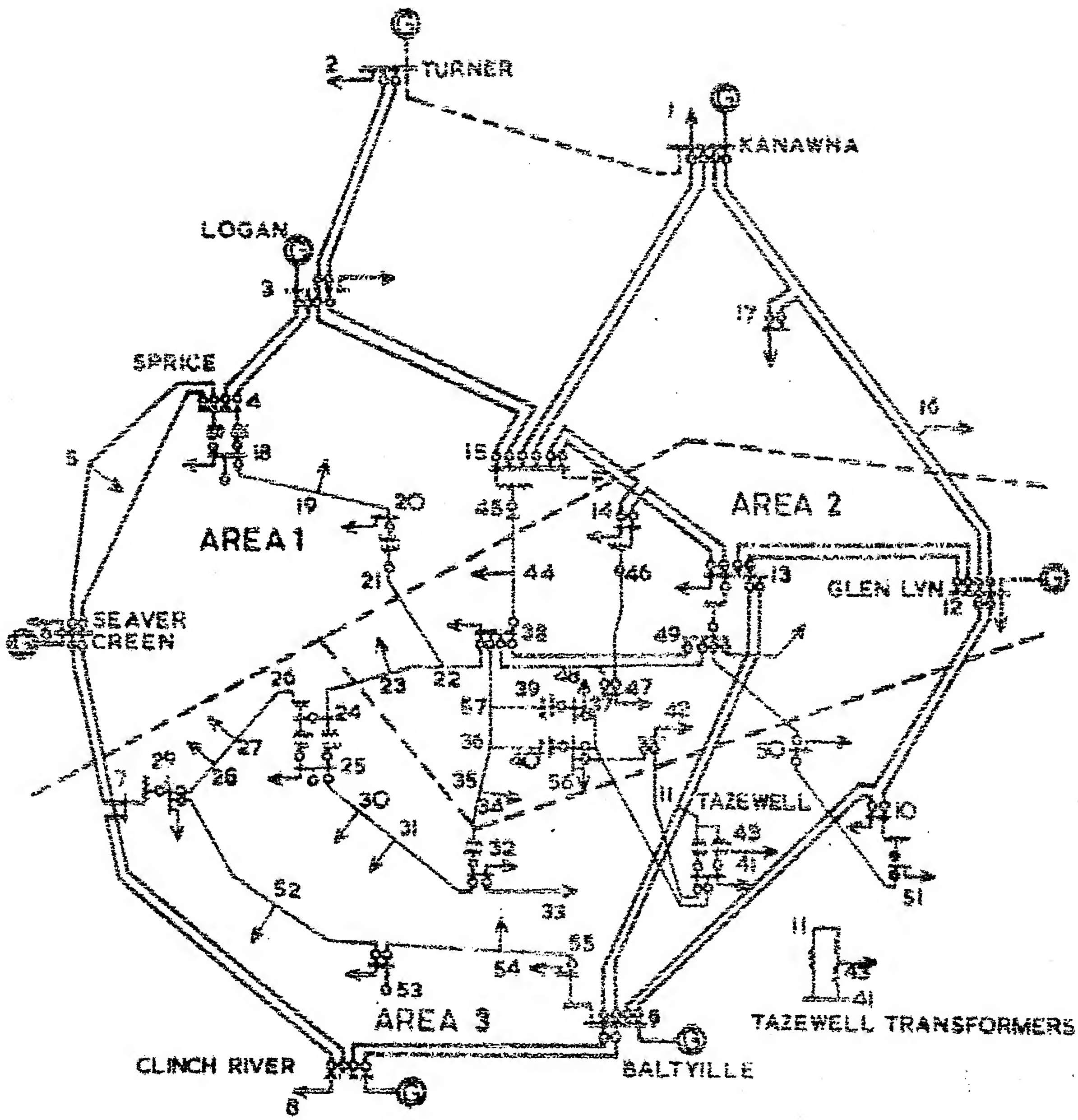


FIG. 5.4 IEEE 57-BUS SYSTEM DECOMPOSED INTO 3 AREAS.

TABLE 5.1 COMPUTATIONAL COMPARISON OF LOAD FLOW SOLUTION BETWEEN COMPUTATION WITHOUT DECOMPOSITION AND TWO LEVEL COMPUTATION

IEEE 30 BUS SYSTEM
MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Method	Computation without decomposition		Two level computation					
			System split in two areas			System split in three areas		
	Total No. of iterations	Relative computer time in % on DEC 1090 system	Optimum acceleration factor	Total No.of iterations	Relative computer time in % on DEC 1090 system	Optimum acceleration factor	Total No.of iterations	Relative computer time in % on DEC 1090 system
NM	2	100	1.5	8	177	1.5	9	136
NRM	2	100	1.5	8	158	1.5	9	130
FDLP	2½	100	1.55	13	195	1.55	12	165

TABLE 5.3 EFFECT OF ACCELERATION FACTOR ON THE NUMBER OF ITERATIONS FOR CONVERGENCE

IEEE 57 BUS SYSTEM SPLIT IN TWO AREAS

MISMATCH < 0.01 P.U. MW AND 0.01 P.U. MVAR

Acceleration factor	Total number of load flow iterations for convergence		
	NM	NRM	FDLP
1.0	15	15	21
1.1	12	13	18
1.2	10	11	15
1.3	9	9	13
1.4	8	8	11
1.5	9	10	10
1.6	11	12	16

TABLE 5.4 OPTIMAL LOAD LOW RESULTS USING TWO LEVEL COMPUTATION

IEEE 30 BUS SYSTEM

	System split in two areas		System split in three areas	
	Initial schedule	Optimal schedule	Initial schedule	Optimal schedule
Real power generation (MW)				
P_{G2}	80.00	50.33	80.00	50.19
P_{G5}	50.00	22.78	50.00	22.13
P_{G8}	20.00	19.82	20.00	19.61
P_{G11}	20.00	15.02	20.00	15.61
P_{G13}	20.00	14.68	20.00	14.21
Voltage magnitude (p.u.)				
V_1	1.05	1.05	1.05	1.05
V_2	1.045	1.018	1.045	1.026
V_5	1.01	1.001	1.01	1.009
V_8	1.01	1.016	1.01	1.012
V_{11}	1.05	1.079	1.05	1.072
V_{13}	1.05	1.082	1.05	1.081
Transformer tap setting				
t_{11}	0.978	1.002	0.978	1.008
t_{12}	0.969	0.946	0.969	0.969
t_{15}	0.932	1.014	0.932	0.932
t_{36}	0.968	0.962	0.968	0.954
Total power generation				
MW	288.800	292.98	288.79	292.74
MVAR	111.61	125.15	110.64	123.42
Total generation cost £ per hr	900.781	804.603	900.767	803.807

TABLE 5.5 OPTIMAL LOAD FLOW RESULTS USING TWO LEVEL COMPUTATION

IEEE 57 BUS SYSTEM

	System split in two areas		System split in three areas	
	initial schedule	optimal schedule	initial schedule	optimal schedule
Real power generation (MW)				
P_{G2}	40.00	100.00	40.00	100.00
P_{G3}	0.00	106.40	0.00	106.16
P_{G6}	0.00	100.30	0.00	100.16
P_{G8}	450.00	154.56	450.00	152.12
P_{G9}	0.00	300.00	0.00	300.00
P_{G12}	310.00	63.22	310.00	61.96
Bus voltage magnitude (p.u.)				
V_1	1.04	1.035	1.04	1.038
V_2	1.01	1.041	1.01	1.045
V_3	0.985	1.027	0.985	1.032
V_6	0.98	1.012	0.98	1.015
V_8	1.005	1.000	1.005	1.000
V_9	0.98	1.003	0.98	1.006
V_{12}	1.015	0.996	1.015	0.999
Total power generation				
MW	1281.03	1289.45	1281.29	1289.66
MVAR	308.81	325.81	309.24	325.32
Total generation cost £ per hr	8443.998	4776.553	8445.469	4775.939

TABLE 5.6 COMPUTATIONAL COMPARISON OF OPTIMAL LOAD FLOW SOLUTION BETWEEN COMPUTATION WITHOUT DECOMPOSITION AND TWO LEVEL COMPUTATION

IEEE 30 BUS AND 57 BUS SYSTEMS

System	Computation without decomposition		Two level computation			
			System split in two areas		System split in three areas	
	Total No. of gradient steps	Relative computer time in % on DEC 1090 system	Total No. of gradient steps	Relative computer time in % on DEC 1090 system	Total No. of gradient steps	Relative computer time in % on DEC 1090 system
IEEE 30 bus	13	100	13	125	13	105
IEEE 57 bus	17	100	17	102	16	76

The optimal load flow results are given in Tables 5.4 to 5.6. The optimum values of the control variables together with generation cost are given in Tables 5.4 and 5.5. Table 5.6 gives the total number of gradient steps and the relative CPU time in %. NM is used for obtaining the load flow solution at each gradient step. In all the above calculations, acceleration is used at the first level. The optimal load flow results obtained using computation without decomposition have been given in the preceding chapter (vide Tables 4.2 and 4.3).

A study of the results presented in Tables 5.1 to 5.6 reveals the following points.

A. Load flow

1) The computational time per load flow iteration of the proposed method is faster than by the method without decomposition.

2) The proposed method takes more number of iterations for the load flow solution compared to the method without decomposition.

3) The computing time per iteration, total number of iterations and hence the overall computer time vary with the number of areas into which the system is decomposed. The convergence rate is adjustable and depends on the value of the acceleration factor used. The optimum acceleration factor changes slightly with the number of areas and the type of the load flow technique used. However, its value is found to be between 1.4

to 1.6 for the different systems studied. This value is similar to that used in Gauss-Seidel load flow.

4) In general, the total computer time using NM, NRM and FDLP load flow techniques is comparable to that of computation without decomposition.

B. Optimal load flow

1) The results obtained agree very well compared to those using computation without decomposition.

2) The number of gradient steps needed to reach the optimal solution is nearly the same as compared to the method without decomposition.

3) The total number of λ-iterations depends on the acceleration factor used and the number of areas. Its optimum value is found to be between 1.4 to 1.6 as in the case of Gauss-Seidel load-flow.

4) The overall computer time is comparable, when the system is solved as a whole or decomposed.

5.5 CONCLUSION

A two level formulation is used for the analysis of load flow and optimal load flow in large scale power systems. The attractive features of the technique are that

i) the optimization of both real and reactive power is possible.

ii) the computational advantages of sparse matrix techniques are exploited in the analysis of areas.

iii) there is a significant reduction in the computer storage, since now, we have to store only the network matrices for each area

iv) the data transmitted between the area computers and pool computer is reduced.

v) the overall computer time is comparable to that of computation without decomposition.

CHAPTER VI

CONVERGENCE CHARACTERISTICS OF THE NEW LOAD FLOW SOLUTION METHODS

6.1 INTRODUCTION

We have presented three load flow solution methods namely, FDLR, NRM and NETR in Chapter II. In this chapter, we study the convergence characteristics of the proposed methods to examine the existence and uniqueness of solutions. Following the lines of Wu [33], the proposed load flow solution methods are represented individually in the form of a nonlinear iterative scheme. Then, the convergence conditions are derived based on the convergence theorem which has been obtained from the fixed point and generalized mean value theorems. Some observations about these conditions of convergence and uniqueness of solutions for the proposed load flow methods and also FDLP are made based on the test results obtained on the IEEE 14 bus test system with different R/X ratio of a transmission line. Before deriving and verifying the convergence conditions for the proposed methods, a few existing studies available on the convergence analysis are briefly reviewed.

6.2 REVIEW OF STUDIES ON CONVERGENCE ANALYSIS PROBLEM

Meisel and Barnard [12] investigated the convergence characteristics of NM and modified NM based on Kantorovich theorem. Korsak [18] gave the definition and stability of the

load flow solutions and analysed the possibility of more than one stable solution. Wu [33] presented a theoretical study of the convergence characteristics of FDLP. He showed that the convergence conditions are dependent on R/X ratios of the transmission lines, scheduled power injections etc. Two alternate upper bounds for the contraction mapping constant, which is merely a number calculated to examine the convergence conditions have been derived. However, these bounds provide highly conservative estimate for the convergence region. Recently, Johnson [35] discussed the multiple and false solutions of the load flow problem. He reported that false solutions may occur due to a system having heavily loaded high voltage lines or generators feeding capacitive loads. Abe et al [38] investigated theoretically the convergence region of NM in the polar and rectangular versions. The necessary conditions for NM to converge to a stable solution under certain operating conditions are given. Successful convergence is reported for the cases having large phase angle corrections but not corrected in the 1st iteration. They have concluded that the load flow convergence will be degraded if a starting value for the voltage less than the flat value is chosen.

6.3 NONLINEAR ITERATIVE SCHEME

As given in reference [33], we wish to solve a system of n equations $\hat{f}_i\ (x_1, x_2, \ldots x_n) = Z_i$; $i = 1, 2, \ldots n$ in n unknowns. In vector form, the system of equations are represented by

$$\hat{F}(x) = Z \tag{6.1}$$

The suitable recursion formula to obtain the solution of $\hat{F}(x) = Z$ is

$$x^{k+1} = \phi(x^k) \tag{6.2}$$

This generates a sequence of points $(x^1, x^2, \ldots)$ which converge to the solution point x^s of the given system of equations. Hence, at the solution point

$$x^s = \phi(x^s) \tag{6.3}$$

the solution of $\hat{F}(x) - Z = 0$ must satisfy $x - \phi(x) = 0$.

Hence, we consider the following relation,

$$\hat{F}(x) - Z = [A(x)]\,(x - \phi(x)) \tag{6.4}$$

where $[A(x)]$ is a nonsingular matrix of order nxn and the elements of $[A(x)]$ are functions of x.

Equation (6.4) can be written as

$$\phi(x) = x - [A(x)]^{-1}\,(\hat{F}(x) - Z) \tag{6.5}$$

Thus, the general form of iterative scheme is given by

$$x^{(k+1)} = x^{(k)} - [A(x)^{(k)}]^{-1}\,(\hat{F}(x)^{(k)} - Z) \tag{6.6}$$

Depending on the particular choice of the matrix $[A(x)]$, different algorithms are obtained. Generally, the load flow algorithms can be regarded as a nonlinear iterative scheme of the form given by (6.6).

We express the proposed new load flow algorithms into the

above general nonlinear iterative scheme as indicated in the following section.

6.3.1 FDLR - as a nonlinear iterative method

The final load flow equations as given in Chapter II, Section 2.4 are

$$[\Delta P] = [B'] \; [\Delta f] \tag{6.7}$$

$$[e] = ([V^2] - [f^2])^{\frac{1}{2}} \tag{6.8}$$

$$[\Delta Q] = [B''] \; [\Delta e] \tag{6.9}$$

The iterative algorithm is given by

$$\left[\begin{array}{c} f^{k+1} \\ \hline e^{k+1} \end{array}\right] = \left[\begin{array}{c} f^{k} \\ \hline e^{k} \end{array}\right] + \left[\begin{array}{c|c} [B']^{-1} & 0 \\ \hline 0 & [B'']^{-1} \end{array}\right] \left[\begin{array}{c} -\Delta P(f^k, e^k) \\ \hline -\Delta Q(f^{k+1}, e_v^{k+1}, e^k) \end{array}\right] \tag{6.10}$$

Comparing equations (6.6) and (6.10), we get

$$[A(x)^k] = \left[\begin{array}{c|c} [B'] & 0 \\ \hline 0 & [B''] \end{array}\right]$$

In the evaluation of $[\Delta Q]$, newly evaluated $[f]$ from equation (6.7) and $[e_v]$ from equation (6.8) are used. The matrix $[A(x)]$ is constant and contain only the network susceptances.

6.3.2 NRM - as a nonlinear iterative method

Using equation (2.46) given in Chapter II, Section 2.5, the iterative algorithm is expressed as

$$\begin{bmatrix} \theta^{k+1} \\ \hline V^{k+1} \end{bmatrix} = \begin{bmatrix} \theta^{k} \\ \hline V^{k} \end{bmatrix} - [J^{(0)}]^{-1} \cdot \begin{bmatrix} -\Delta P(\theta^k, V^k) \\ \hline -\Delta Q(\theta^k, V^k) \end{bmatrix}$$

$$- [J^{(0)}]^{-1} \left\{ \begin{bmatrix} -\Delta P(\theta^k, V^k) \\ \hline -\Delta Q(\theta^k, V^k) \end{bmatrix} - [J^{(k)}][J^{(0)}]^{-1} \begin{bmatrix} -\Delta P(\theta^k, V^k) \\ \hline -\Delta Q(\theta^k, V^k) \end{bmatrix} \right\} - \ldots \tag{6.11}$$

i.e.

$$\begin{bmatrix} \theta^{k+1} \\ \hline V^{k+1} \end{bmatrix} = \begin{bmatrix} \theta^{k} \\ \hline V^{k} \end{bmatrix} - [J^{(0)}]^{-1} \begin{bmatrix} -\Delta P'(\theta^k, V^k) \\ \hline -\Delta Q'(\theta^k, V^k) \end{bmatrix}$$

Comparing equation (6.11) with (6.6), we obtain

$$[A(x)^k] = [J^{(0)}]$$

The algorithm therefore, is a fixed Jacobian Newton algorithm with modified power injection equations.

6.3.3 NETR - as a nonlinear iterative method

The final load flow equations as given in Chapter II, Section 2.6 are

$$\left[\frac{\Delta P_v}{V_v}\right] = [B'_R]\,[\Delta\theta_v] \tag{6.12}$$

$$[Y'_{LL}]\,[E_L] = -[Y_{LG}]\,[E_G] \tag{6.13}$$

Equation (6.12) refers to an equivalent system consisting of only P-V buses.

Equations (6.12) and (6.13) can be written as

$$[\Delta P_v] = [V_v \cdot B'_R]\,[\Delta\theta_v] \tag{6.14}$$

$$[E_L] = [E_L] - [Y'_{LL}]^{-1}\,[Y_{LG}]\,[E_G] - [E_L] \tag{6.15}$$

Using equations (6.14) and (6.15), the iterative algorithm can be written as

$$\left[\begin{array}{c} \theta_v^{k+1} \\ \hline E_L^{k+1} \end{array}\right] = \left[\begin{array}{c} \theta_v^{k} \\ \hline E_L^{k} \end{array}\right] - \left[\begin{array}{c|c} [V_v \cdot B'_R]^{-1} & 0 \\ \hline 0 & [Y'_{LL}]^{-1} \end{array}\right] \left[\begin{array}{c} -\Delta P(\theta_v^k, V_v) \\ \hline [Y_{LG}]\,[E_G^{k+1}] + [Y'_{LL}]\,[E_L^k] \end{array}\right] \tag{6.16}$$

Comparing (6.16) with (6.6) we get

$$[A(x)^k] = \left[\begin{array}{c|c} [V_v \cdot B'_R] & 0 \\ \hline 0 & [Y'_{LL}] \end{array}\right]$$

The iterative algorithm for the reduced system consisting of only P-V buses is given by

$$[\theta_v^{k+1}] = [\theta_v^{k}] - [V_v \cdot B'_R]^{-1}\,[-\Delta P(\theta_v^k, V_v)] \tag{6.17}$$

Here,

$$[A(x)^k] = [V_v \cdot B'_R]$$

6.4 CONVERGENCE CONDITIONS

Using the convergence theorem defined in Appendix C, the conditions of convergence for the proposed load flow methods, are presented in this section.

6.4.1 Convergence criterion for FDLR

Suppose the region of interest for finding the solution to load flow problem with a flat voltage start ($e_i + jf_i$ = 1.0 + j0.0) is defined as

$$|f_i| < \hat{\varepsilon} \tag{6.18}$$

$$|e_i - 1| < \hat{\varepsilon} \; ; \quad \text{for } i = 1, 2, \ldots n \tag{6.19}$$

and C_c is the contraction constant given by

$$C_c = \max \quad \| D\,\phi\,(f,e) \|$$

where

$$D\,\phi(f,e) = \left[\begin{array}{c|c} \hat{I} & 0 \\ \hline 0 & \hat{I} \end{array}\right] - \left[\begin{array}{c|c} [B']^{-1} & 0 \\ \hline 0 & [B'']^{-1} \end{array}\right] [J(f,e)] \tag{6.20}$$

Suppose that

i) $C_c < 1$

ii) the initial correction Δf_i^o, Δe_i^o satisfying

$$\max_i \; \{ |\Delta f_i^o| \, , \; |\Delta e_i^o| \} < (1 - C_c)\,\hat{\varepsilon}$$

Then

1) there exists a unique solution within the region defined by (6.18 - 6.19)

2) the iterates (6.7 to 6.9) converge to the solution.

6.4.2 Convergence criterion for NRM

Suppose the region of interest for finding the solution to load flow problem with a flat voltage start is defined by

$$|\theta_i| < \hat{\alpha} \qquad \text{for } i = 1,2, \ldots n \tag{6.21}$$

$$|V_i - 1| < \hat{\varepsilon} \qquad \text{for } i = m+1 \ldots n \tag{6.22}$$

and C_c is the contraction constant given by

$$C_c = \max \quad ||D\,\phi\ (\theta, V)\,||$$

where

$$D\,\phi(\theta,V) = \left[\begin{array}{c|c} \hat{I} & 0 \\ \hline 0 & \hat{I} \end{array}\right] - [J^{(0)}]^{-1} \quad [J(\theta,V)] \tag{6.23}$$

Suppose that,

i) $C_c < 1$

ii) the initial correction $\Delta\theta_i^o$, ΔV_i^o satisfying

$$\max_i \{\ \hat{\varepsilon}/\hat{\alpha}|\ \Delta\theta_i^o| \ ,\ \ |\Delta V_i^o|\} < (1-C_c)\,\hat{\varepsilon}$$

Then,

1) there exists a unique solution within the region defined by (6.21 - 6.22).

2) the iterates (6.11) converge to the solution.

6.4.3 Convergence criterion for NETR

Here, the conditions are derived for an equivalent system consisting of only P-V buses.

Suppose the region of interest for finding the solution to load flow problem with a flat voltage start is defined by

$$|\theta_i| < \hat{\alpha} \qquad \text{for } i = 1,2, \ldots n \tag{6.24}$$

$$|V_i - 1| < \hat{\varepsilon} \qquad \text{for } i = m+1 \ \ldots n \tag{6.25}$$

and C_{cr} is the contraction constant given by

$$C_{cr} = \max \ || \ D\,\phi\,(\theta_v, V_v)\ ||$$

where

$$D\phi\,(\theta_v, V_v) = [\hat{I}] - [V_v \ . \ B'_R]^{-1}\,[J(\theta_v, V_v)] \tag{6.26}$$

and the subscript r refers to the reduced system.

In the above equation, $[V_v]$ the voltage magnitude vector relating to the P-V buses is specified.

Suppose that

i) $C_{cr} < 1$

ii) the initial correction $\Delta\theta^o_{vi}$ satisfying

$$\max_i \left\{\frac{\hat{\varepsilon}\,|\Delta\theta^o_{vi}|}{\hat{\alpha}}\right\} < (1 - C_{cr})\,\hat{\varepsilon}$$

then,

1) there exists a unique solution within the region defined by (6.24 - 6.25)
2) the iterates (6.12 and 6.13) converge to the solution.

6.5 SYSTEM STUDIES

The convergence conditions derived in the preceding section pertaining to the proposed load flow methods have been tested on the IEEE 14 bus test system with different R/X ratio of a transmission line. The maximum values of the contraction mapping constant C_c at any particular iteration obtained using the proposed methods as well as FDLP are tabulated in Table 6.1.

Discussion of the results

The values of the contraction mapping constant C_c are less than 1 for all the proposed methods on the IEEE 14 bus test system when the line resistances are neglected. These values are more than 1 for FDLR and less than or comparable to 1 for NRM and NETR when the line resistances are not neglected and R/X ratio of a heavily loaded line is increased on the IEEE 14 bus system. The C_c values obtained by using FDLR for the different cases studied are comparable to those obtained by using FDLP. Therefore, it is concluded that the convergence of FDLR is dependent on R/X ratios of the transmission lines as in FDLP, whereas it is independent for NRM and NETR as in NM. That means, when R/X ratio is small,

TABLE 6.1 CONTRACTION CONSTANT FOR THE LOAD FLOW SOLUTION METHODS

IEEE 14 BUS SYSTEM

Method	Contraction constant C_c			
	IEEE 14 bus system with all the resistance values neglected	IEEE 14 bus system	IEEE 14 bus system with R/X ratio of the heavily loaded line 1 increased by 2 times	IEEE 14 bus system with R/X ratio of the heavily loaded line 1 increased by 5 times
FDLP	0.562	1.945	1.993	2.354
FDLR	0.744	2.243	2.282	2.764
NRM	0.585	0.793	0.805	1.027
NETR	0.170	0.209	0.214	0.397

faster convergence may be obtained by using FDLR, similar to FDLP, This fact has already been proved by the test results given in Chapter II, Section 2.7. For the systems having transmission lines with fairly large R/X ratios, the larger values of C_c for both FDLP and FDLR indicate that there may be convergence difficulties. This conclusion is similar to that reported for FDLP in reference [33].

6.6 CONCLUSION

In this chapter, we have derived convergence conditions for the proposed FDLR, NRM and NETR load flow methods following Wu's approach [33]. The convergence of FDLR is degraded when R/X ratios of the transmission lines are increased, which is similar to that for FDLP. The convergence of NRM or NETR is unaffected with higher R/X ratios of the transmission lines as in NM.

CHAPTER VII

CONCLUSION

7.1 GENERAL

This thesis has been aimed at developing improved solution methods for power system studies involving the load flow, contingency evaluation and optimal power dispatch and two level techniques for the load flow and optimal load flow based on decomposition and multicomputer configurations.

We shall first review the significant results obtained due to the various suggested methods and then give the scope for further research.

7.2 REVIEW OF THE SIGNIFICANT RESULTS

Load flow :

In Chapter II, three new load flow solution methods namely, FDLR, NRM and NETR have been proposed.

i) FDLR has been derived using linear transformation from FDLP as well as direct from NM.

ii) NRM has been developed using the simplified NM and Newton-iterative methods.

iii) NETR has been developed based on network reduction techniques and NRM.

From the test results, it is concluded that the above

methods have certain superior features compared to the existing widely used methods. These features are summarized below :

i) FDLR is best suited for moderately accurate solutions compared to FDLP with 5 to 10% overall saving in computer time. The memory storage requirements are similar to FDLP.

ii) NRM is about two times faster than NM and with the availability of Jacobian, it is an attractive alternative where NM is preferred.

iii) NETR is a comparable alternative to FDLP in terms of computational speed and core storage for medium size systems with convergence characteristics similar to NM.

Contingency Evaluation :

The proposed FDLR and NETR load flow techniques have been extended for contingency evaluation in Chapter III. In the FDLR algorithm, the matrix inversion lemma has been used whereas in the NETR algorithm, the matrix inversion lemma and matrix updating algorithm have been used to make use of the base case factors for the simulation of the different outage cases as in prevalent competing methods [29,57]. Digital simulation and comparison have shown that :

i) FDLR is superior in computational speed by about 10 to 20% over FDLP.

ii) N_TR is comparable or faster than FDLP in terms of speed, depending on the number of P-V buses in the system.

iii) the average error in the line real power flows is comparable to FDLP for the different proposed iterative schemes using FDLR and NETR.

Optimal load flow and economic dispatch :

In Chapter IV, the OLF and economic dispatch problems have been solved. In the OLF problem, the equations pertaining to the load flow and Lagrangian multipliers have been solved by using NRM. In the economic dispatch algorithm using NETR, the optimization has been carried out on the reduced system consisting of only P-V buses, based on the assumption that the real power schedules do not change significantly the load bus voltages. Numerical computation and comparison have shown that :

i) there is an overall saving in computer time of more than 50% when NRM is used in the place of NM using the method of Dommel and Tinney [65], without affecting the convergence characteristics, accuracy and general formulation of the problem. Although, it is comparable to the method using FDLP [72] in terms of computing speed, the Jacobian is available for further applications.

ii) the approach by NETR for economic dispatch results in a great saving in computer time of about 80% over the method of approach by NM [65] and hence is competitive to

the method using FDLP [72]. This shows the feasibility of this method for real-time applications.

Two level solutions :

In Chapter V, a two level optimization procedure has been developed for large scale power system optimization problem. In the proposed technique, both real and reactive power optimization have been carried out, considering the adjustable real power generations, voltage magnitude of generators and transformer tap ratios as control variables. This has been achieved by introducing pseudo variables. The original system has been split into a number of areas by the cut-lines. The area optimal solutions have been obtained at the first level and the coordinating pseudo variables and the associated Lagrange multipliers have been solved at the second level. Two level load flow procedures using NM, NRM and FDLP techniques have also been indicated. It is established that the proposed two level techniques give good results, for the load flow as well as OLF problems. The numerical results have shown that :

i) the convergence characteristics of the two level technique are dependent on the acceleration factor used and the number of areas into which the original system is decomposed.

ii) in comparison with the computation without decomposition, the results obtained and the overall computer time are comparable.

Convergence analysis :

A theoretical analysis of the convergence characteristics of the proposed FDLR, NRM and NETR load flow iterative schemes, following the procedure indicated by Wu [33], has been made in Chapter VI, to examine the existence and uniqueness of solutions in a specified region. The convergence conditions have been derived and verified on the IEEE 14 bus test system with different R/X ratio of the heavily loaded line. The test results have shown that :

i) there may be convergence difficulties encountered, with large R/X ratios of the transmission lines using FDLR. This is similar to as reported for FDLP.

ii) the convergence of NRM or NETR is not affected by the R/X ratios of the transmission lines as in NM.

7.3 SCOPE FOR FURTHER RESEARCH

In reference [110], a new algorithm called calibration load flow (CALF) based on FDLP has been proposed which is suitable for the real-time implementation of security functions such as interconnection modelling and tie-line flow matching. The possibility of using FDLR or NETR in the place of FDLP with computational advantages should be examined.

It should be possible to extend the two level technique proposed in Chapter V for contingency evaluation. This work needs further investigation.

In the economic dispatch solution procedure using NETR proposed in Chapter IV, the line security constraints have not been considered. The inclusion of these additional constraints may pose difficulty. This needs to be examined further.

LIST OF REFERENCES

1. H.E. Brown, G.K. Carter, H.H. Happ and C.E. Person, "Power flow solution by impedance matrix iterative method", AIEE Trans. PAS. Vol. 82, Part III, pp.1-10, April 1963.

2. W.F. Tinney and C.E. Hart, "Power flow solution by Newton's method", IEEE Trans. PAS. Vol. 86, pp.1449-1460, November 1967.

3. W.F. Tinney and J.W. Walker, "Direct solutions of sparse network equations by optimally ordered triangular factorization", Proc. IEEE, Vol. 55, pp.1801-1809, November 1967.

4. R.G. Andretich, H.E. Brown, H.H. Happ and C.E. Person", "The piecewise solution of the impedance matrix load flow", IEEE Trans. PAS. Vol. 87, pp.1877-1882, October 1968.

5. M.A. Laughton, "Decomposition techniques in power system network load flow analysis using the nodal-impedance matrix", Proc. IEE, Vol.115, No.4, pp.539-542, April 1968.

6. H.E. Brown, G.K. Carter, H.H. Happ and C.E. Person, "Z-matrix algorithms in load flow programs", IEEE Trans. PAS. Vol. 87, pp. 807-814, March 1968.

7. Y. Wallach, "Gradient methods for load flow problems", IEEE Trans. PAS. Vol. 87, pp.1314-1318, May 1968.

8. L.L. Freris and A.M. Sasson, "Investigation of the load flow problem", Proc. IEE, Vol. 115, pp.1459-1470, October 1968.

9. G.W. Stagg and A.H. El-Abiad, "Computer methods in power system analysis", (Book), McGraw-Hill, 1968.

10. A.M. Sasson, "Nonlinear programming solutions for the load flow, minimum loss and economic dispatch problems", IEEE Trans. PAS. Vol. 88, pp.399-409, April 1969.

11. H.H. Happ, "Diakoptics and piecewise methods", IEEE Trans.PAS.Vol.89,pp.1373-1382, September/October 1970.

12. J. Meisel and R.D. Barnard, "Application of fixed point techniques to load flow studies", IEEE Trans. PAS. Vol.89, pp. 136-140, January 1970.

13. J.M. Ortega and W.C. Rheinbolt, "Iterative solution of non-linear equations in several variables", (Book), Academic Press, 1970.

14. R.G. Andretich, H.E. Brown, D.H. Hansen and H.H. Happ, "Piecewise load flow solutions of very large size networks", IEEE Trans. PAS. Vol. 90, pp. 950-961, May/June 1971.

15. Yehuda Wallach, Ezra K. Even and Yaakov Yavin, "Improved methods for load flow calculations", IEEE Trans. PAS. Vol. 90, pp.116-122, January 1971.

16. S.T. Despotovic, B.S. Babic and V.P. Mastelovic, "A rapid and reliable method for solving load flow problems", IEEE Trans. PAS. Vol. 90, pp. 123-130, January 1971.

17. Y.P. Dusonchet, S.N. Talukdar, H.E. Sinnot and A.H. El-Abiad, "Load flows using a combination of point Jacobi and Newton's methods", IEEE Trans. PAS. Vol. 90, pp. 941-949, May/June 1971.

18. A.J. Korsak, "On the question of uniqueness of stable load flow solution", IEEE Trans. PAS. Vol.91, pp. 1093-1100, May/June 1972.

19. B. Stott, "Decoupled Newton load flows", IEEE Trans. PAS. Vol. 91, pp.1955-1959, September/October 1972.

20. C.H. Jolissaint, N.V Arvanitidis and D.G Luenberger, "Decomposition of real and reactive power flows: A method suited for on-line applications", IEEE Trans. PAS. Vol. 91, pp. 661-670, March 1972.

21. O.J.M. Smith, Kalpana Makani and Lakshmi Krishna, "Sparse solutions using hash storage", IEEE Trans. PAS. Vol. 91, pp. 1396-1404, July 1972.

22. S.T.Y. Lee, "Transient stability equivalents for power system planning", Ph.D. Thesis, Massachusetts Institute of Technology, 1972.

23. D.A. Conner, "Representative Bibliography on load flow analysis and related topics", presented at the IEEE PES Winter Meeting, New York, Paper C 73104-7, February 1973.

24. W.F. Tinney, "Sparsity oriented network reduction", PICA Conference Proc., pp. 384-390, 1973.

25. B. Stott, "Review of load flow calculation methods", Proc. IEEE, Vol. 62, No.7, pp. 916-929, July 1974.

26. T.E. DyLiacco, "Real-time computer control of power systems", Proc. IEEE, Vol. 62, No.7, pp. 884-891, July 1974.

27. H.H. Happ, "Diakoptics - the solution of system problems by tearing", Proc. IEEE, Vol. 62, No.7, pp. 930-940, July 1974.

28. S.T. Despotovic, "A new decoupled load flow method", IEEE Trans. PAS. Vol. 93, pp. 884-891, May/June 1974.

29. B. Stott and O. Alsac, "Fast decoupled load flow", IEEE Trans. PAS. Vol. 93, pp. 859-869, May/June 1974.

30. M. Okamura, Y. O-ura, S. Hayashi, K. Uemura, and F. Ishiguro, "A new power flow model and solution method, including load and generator characteristics and effects of system control devices", IEEE Trans. PAS. Vol. 94, pp. 1042-1050, May/June 1975.

31. M.S. Sachdev and T.K.P. Medicherla, "A second order load flow technique", IEEE Winter Power Meeting, January 1976; IEEE Trans. PAS. Vol. 96, pp. 189-197, January/February 1977.

32. T.K.P. Medicherla and M.S. Sachdev, "A second order decoupled load flow technique", Paper presented at IEEE Summer Power Meeting, A76491-1, July 1976.

33. F.F. Wu, "Theoretical study of the convergence of the fast decoupled load flow", IEEE Trans. PAS. Vol. 96, pp. 268-275, January/February 1977.

34. S. Elangovan, V. Sankaranarayan and M. Venugopal, "Power flow solution by the method of reduction and restoration", Paper presented at IEEE PES Winter Meeting, 1977.

35. B.K. Johnson, "Extraneous and false load flow solutions", IEEE Trans. PAS. Vol. 96, pp. 524-534, March/April 1977.

36. G.J. Berg, P. Subramanian and K.R.C. Mamandur, "Efficient load flow algorithm", Paper presented at IEEE PES Winter Meeting, A78068-9, 1978.

37. A.H. Sherman, "On-Newton-iterative methods for the solution of systems of nonlinear equations", Siam Journal on Numerical Analysis, pp. 755-771, August 1978.

38. S. Abe, N. Hamada, A. Isono and K. Okuda, "Load flow convergence in the vicinity of a voltage stability limit", IEEE Trans. PAS. Vol. 97, pp. 1983-1993, November 1978.

39. M.J.H. Sterling, "Power system control", (Book), IEE Control Engineering Series 6, 1978.

40. S. Iwamota and Y. Tamura, "A fast load flow method retaining nonlinearity", IEEE Trans. PAS. Vol. 97, pp. 1586-1599, September 1978.

41. T.E. DyLiacco, "System security: the computer's role", IEEE Spectrum, pp. 43-50, June 1978.

42. M. El-Marsafawy, R.W. Menzies and R.M. Mathur, "A new, exact, diakoptic, fast decoupled load flow technique for very large power systems", Paper presented at IEEE PES Summer Meeting, A79440-9, 1979.

43. M.A. Pai, R.P. Aggarwal and N. Arumugam, "A fast algorithm for on-line load flow and contingency evaluation", IFAC International Symposium on 'Computer Applications in Large Scale Power Systems', New Delhi, Vol. I (Book), pp. 132-138, August 1979.

44. M.A. Pai, "Computer techniques in power system analysis", (Book), Tata McGraw-Hill Publishing Company, 1979.

45. R.P. Aggarwal, M.A. Pai and N. Arumugam, "Load flow solution by Newton-Richardson method and its adaptation to optimal load dispatch", Paper accepted for publication in the International Journal of Electrical Power and Energy Systems, England, 1980.

46. A.F. Glimm and G.W. Stagg, "Automatic calculation of load flows", AIEE Trans. PAS, Vol. 76, pp. 817-828, October 1957.

47. C.A. MacArthur, "Transmission limitations computed using superposition", AIEE Trans. PAS. Vol. 80, Part III, pp. 827-831, 1961.

48. A.H. El-Abiad and G.W. Stagg, "Automatic evaluation of power system performance - Effect of line and transformer outages", AIEE Trans. PAS. Vol. 81, pp. 712-716, 1963.

49. H.D. Limmer, "Techniques and applications of security calculations applied to dispatching computers", Paper No. STY4, Proc. Power System Computation Conference, Rome, Italy, June 1969.

50. H.E. Brown, "Contingencies evaluated by a Z-matrix method", IEEE Trans. PAS. Vol. 88, pp. 409-412, 1969.

51. L.P. Hajdu, D.W. Bree and A.W. Brooks, "On-line monitoring of power system security", Paper presented at IEEE Summer Meeting, No. 70CP690-PWR, July 1970.

52. G.W. Stagg and A.G. Phadke, "Real-time evaluation of power system contingencies - detection of steady state overloads", Paper presented at IEEE Summer Power Meeting, No. 70CP692-PWR, July 1970.

53. K. Uemura, "Power flow solution by a Z-matrix type method and its application to contingency evaluation", PICA Conference Proc. pp. 386-390, May 1971.

54. A.G. Dewey and W.G. Tuel, "Power system security indices", PICA Conference Proc. pp. 365-373, 1971.

55. H. Daniels and Mo-Shing Chen, "An optimization technique and security calculations for dispatching computers", IEEE Trans. PAS. Vol. 91, pp. 883-888, May/June 1972.

56. W.F. Tinney, "Compensation methods for networks solutions by optimally ordered triangular factorization", IEEE Trans. PAS. Vol. 91, pp. 123-128, January/February 1972.

57. N.M. Peterson, W.F. Tinney and D.W. Bree, Jr., "Iterative linear AC power flow solution for fast approximate outage studies", IEEE Trans. PAS. Vol. 91, pp. 2048-2056, September/October 1972.

58. M.S. Sachdev and S.A. Ibrahim, "A fast approximate technique for outage studies in power system planning and operation", IEEE Trans. PAS. Vol. 93, pp. 1133-1142, July/August 1974.

59. M.A. Pai and M.A. Khan, "An efficient algorithm for outage studies in power systems based on sensitivity approach", Paper presented at IEEE Summer Power Meeting, No.C74327-3, 1974.

60. H.E. Brown, "Low voltages caused by contingencies predicted by a high speed Z-matrix method", IEEE Trans. PAS. Vol. 96, pp. 44-51, January/February 1977.

61. M.S. Sachdev and S.A. Ibrahim, "A modified Newton-Raphson load flow formulation and a line/transformer outage simulation technique", Paper presented at IEEE Winter Power Meeting, A79021-7, 1979.

62. G.C. Ejebe and B.F. Wollenberg, "Automatic contingency selection", IEEE Trans. PAS. Vol. 98, pp. 97-109, January/February 1979.

63. M.A. Pai, R.P. Aggarwal and N. Arumugam, "A comparative study of contingency evaluation methods for on-line power system security", Diamond Jubilee Symposium on 'optimization of electrical apparatus and systems', (Book), B.H.U., India, pp. 94-99, March 1979.

64. J. Carpentier, "Contribution to the economic dispatch problem", (in French), Bull. Soc. Franc. Elect. Vol.8, pp. 431-447, August 1962.

65. H.W. Dommel and W.F. Tinney, "Optimal power flow solutions", IEEE Trans. PAS. Vol. 87, pp. 1866-1876, October 1968.

66. A.M. Sasson, "Combined use of the Powell and Fletcher Powell non-linear programming methods for optimal load flows", IEEE Trans. PAS. Vol. 88, pp. 1530-1537, October 1969.

67. A.M. Sasson, F. Aboytes, R. Cardenas, G. Gomez and F. Viloria, "A comparison of power systems static optimization techniques", PICA Conference Proc., pp. 329-337, May 1971.

68. A.M. Sasson, F. Viloria and F. Aboytes, "Optimal load flow solution using the Hessian matrix", IEEE Trans. PAS. Vol. 92, pp. 31-41, January/February 1973.

69. R. Billinton and S.S. Sachdeva, "Real and reactive power optimization by suboptimum techniques", IEEE Trans. PAS. Vol. 92, pp. 950-956, May/June 1973.

70. A.M. Sasson and H.M. Merril, "Some applications of optimization techniques to power system problems", Proc. IEEE, Vol. 62, No.7, pp. 959-972, July 1974.

71. A.M.H. Rashed and D.H. Kelley, "Optimal load flow using Lagrangian multipliers and the Hessian matrix", IEEE Trans. PAS. Vol. 93, pp. 1292-1297, September/October 1974.

72. O. Alsac, "Load flow and optimal load flow analysis for large power systems", Ph.D. Thesis, The Victoria University of Manchester, May 1974.

73. H.H. Happ, "Optimal power dispatch, A comprehensive survey", IEEE Trans. PAS. pp. 841-854, May/June 1977.

74. J.L. Bala, Jr. and A. Thanikachalam, "An improved second order method for optimal load flow", IEEE Trans. PAS. Vol. 97, pp. 1239-1244, August 1978.

75. L.K. Kirchmeyer, H.H. Happ, G.W. Stagg and J.F. Hohenstein, "Direct calculation of transmission loss formula-I", AIEE Trans. Vol. 79, Pt. III, pp. 962-969, December 1960.

76. H.H. Happ, J.F. Hohenstein, L.K. Kirchmayer, and G.W. Stagg, "Direct calculation of transmission loss formula-II", IEEE Trans. PAS. Vol. 83, pp. 702-707, July 1964.

77. W.S. Meyer, and V.D. Albertson, "Improved loss formula computation by optimally ordered elimination techniques", IEEE Trans. PAS. Vol. 90, pp. 62-69, January/February 1971.

78. G.F. Reid and W. Hasdorff, "Economic dispatch using quadratic programming", IEEE Trans. PAS. Vol. 92, pp. 2015-2023, November/December 1973.

79. R. Podmore, "A simplified and improved method for calculating transmission loss formulas", PICA Conference Proc., pp. 428-432, 1973.

80. O. Alsac and B. Stott, "Decoupled algorithms in optimal load flow calculations", Paper presented at IEEE PES Summer Meeting, A75545-4, July 1975.

81. C.L. Wadhwa and J. Nanda, "New approach to modified coordination equations for economic load dispatch", IEE Proc., Vol. 123, No.9, pp. 923-925, 1976.

82. J.N. Malik and G.K. Rao, "Economic load dispatch solution using fast decoupled load flow", IEE Proc., Vol. 125, pp. 334-335, April 1978.

83. F.L. Alvarado, "Penalty factors from Newton's method", IEEE Trans. PAS. Vol. 97, pp. 2031-2040, November/December 1978.

84. R.R. Shoults, W.M. Grady and S. Helmick, "An efficient method for computing loss formula coefficients based upon the method of least squares", IEEE Trans. PAS. Vol. 98, pp. 2144-2152, November/December 1979.

85. S.K. Mitter and T.E. DyLiacco, "Multilevel approach to the control of interconnected power systems", Proc. of 2nd IFAC International Conference on 'Digital Applications to Process Control', pp. 114-123, 1967.

86. H.H. Happ, "Multicomputer configurations and diakoptics - Real power flow in power pools", IEEE Trans. PAS. Vol. 88, pp. 764-772, May 1969.

87. H.H. Happ and John M. Undrill, "Multicomputer configurations and diakoptics - Real power flow in power pools", IEEE Trans. PAS. Vol. 88, pp. 789-796, June 1969.

88. J.P. Britton, "Improved area interchange control for Newton's load flow", IEEE Trans. PAS. Vol. 88, pp. 1577-1581, October 1969.

89. M.D. Mesarovic, D. Macko and Y. Takahara, "Theory of hierarchical multilevel systems", (Book), Academic Press, 1970.

90. A.M. Sasson, "Decomposition techniques applied to the nonlinear programming load flow method", IEEE Trans. PAS. Vol. 89, pp. 78-82, January 1970.

91. J.M. Undrill and H.H. Happ, "Automatic sectionalisation of power system networks for network solutions", IEEE Trans. PAS. Vol. 90, pp. 46-53, January/February 1971.

92. A. Brameller and K.L. Lo, "A review of minimization techniques with reference to power system engineering", Proceedings of the symposium on real time control of electric power systems (Book) edited by E. Handschin Elsevier Publishing Company, 1972.

93. H. Kobayashi, "A computational algorithm for multilevel control of system voltage and reactive power", Electrical Engineering in Japan, Vol. 92, pp. 72-80, November/December, 1972.

94. N. Nabona and L.L. Freris, "Optimization of economic dispatch through quadratic and linear programming", IEE Proc. Vol. 120, No.5, pp. 574-580, May 1973.

95. M.K. Jain and N.D. Rao, "A power system network decomposition algorithm for network solutions", IEEE Trans. PAS, Vol. 92, pp. 619-625, March/April 1973.

96. H.H. Happ, "Diakoptics and system operations: automatic generation control in multiareas", IEE Proc. Vol. 120, No.4, pp. 484-490, April 1973.

97. H.H. Happ, "Multilevel tearing and applications", IEEE Trans. PAS. Vol. 92, pp. 725-733, March/April 1973.

98. S. Narita and M.S.A.A. Hammam, "Multicomputer control of system voltage and reactive power on real time basis", IEEE Trans. PAS. Vol. 92, pp. 278-286, January/February 1973.

99. E. Handschin and F.D. Galiana, "Hierarchical state estimation for real time monitoring of electric power systems", PICA Conference Proc., pp. 304-312, 1973.

100. H.H. Happ, "Multicomputer configurations and diakoptics - stability analysis of large power systems", PICA Conference Proc. pp. 101-104, 1973.

101. M.K. Jain, N.D. Rao and G.J. Berg, "Improved area interchange control method with any numerical technique", IEEE Trans. PAS. Vol. 93, pp. 1634-1639, September/October 1974.

102. M.A. Pai and R. Jegatheesan, "An efficient heuristic procedure to decompose power system networks", Paper presented at IEEE Summer Power Meeting, C74341-4, July 1974.

103. S.R. Paranjothi, "Preventive control and diakoptical optimization of large scale power systems", Ph.D. Thesis, I.I.T. Kanpur (India), January 1976.

104. Y.Y. Haimes, "Hierarchical analysis of water resources systems", (Book), McGraw-Hill, 1977.

105. S. Iwamota, "Hierarchical voltage control and reduction of sensitivity matrices for large scale power systems", Electrical Engineering in Japan, Vol. 97, pp. 25-32, May/June 1977.

106. M.J.H. Sterling and M.R. Irving, "Constrained dispatch of active power by linear decomposition", IEE Proc. Vol. 124, No.3, pp. 247-251, 1977.

107. M.R. Irving and H. Nicholson and M.J.H. Sterling, "Hierarchical control of electric power systems", Large scale systems engineering applications, North Holland Publishing Company, pp. 496-515, 1979.

108. M. Bielli and M. Cini, "An application of hierarchical control theory to economic dispatching of electric power", Large scale systems engineering applications, North Holland Publishing Company, pp. 516-539, 1979.

109. R. Divi and H.K. Kesavan, "A piecewise method for optimal load flow problem", IFAC symposium on 'Computer applications in large scale power systems', New Delhi, Vol. III (Book), pp. 84-91, August 1979.

110. K.A. Ramarao, "Introduction model update in real time", IFAC Symposium on 'Computer applications in large scale power systems', New Delhi, Vol. III (Book), pp.150-153, August 1979.

111. P. Groumpos, "Sensitivity analysis of large scale systems via a two level dynamical hierarchical approach", Proceedings of the Third International Symposium on Large Engineering Systems, Canada, pp. 251-254, July 1980.

112. R.P. Aggarwal, M.A. Pai and N. Arumugam, "Load flow and optimal load flow analysis of large scale power systems by a two level computation", Proceedings of the Third International Symposium on Large Engineering Systems, Canada, pp. 293-299, July 1980.

APPENDIX A

ELEMENTS OF THE JACOBIAN MATRIX [J]

A.1 POLAR COORDINATES

The real and reactive power injections at the bus i in terms of the voltage angle and magnitude and the bus admittance matrix elements can be expressed as

$$P_i = V_i \sum_{j=1}^{n} ((G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})V_j) \tag{A.1}$$

$$Q_i = V_i \sum_{j=1}^{n} ((G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})V_j) \tag{A.2}$$

Then, the elements of the Jacobian $[J^p]$ defined in equation (2.6) are as given below :

For $i \neq j$

$$\frac{\partial P_i}{\partial \theta_j} = \frac{\partial Q_i}{\partial V_j} = V_i V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \tag{A.3}$$

$$\frac{\partial P_i}{\partial V_j} = -\frac{\partial Q_i}{\partial \theta_j} = V_i V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \tag{A.4}$$

for $i = j$

$$\frac{\partial P_i}{\partial \theta_i} = - B_{ii} V_i^2 - Q_i \tag{A.5}$$

$$V_i \frac{\partial P_i}{\partial V_i} = G_{ii} V_i^2 + P_i \tag{A.6}$$

$$\frac{\partial Q_i}{\partial \theta_i} = -G_{ii} V_i^2 + P_i \tag{A.7}$$

$$V_i \frac{\partial Q_i}{\partial V_i} = -B_{ii} V_i^2 + Q_i \tag{A.8}$$

A.2 RECTANGULAR COORDINATES

The real and reactive power injections at the bus i in terms of the real and imaginary components of the voltage and bus admittance matrix elements can be expressed as

$$P_i = \sum_{j=1}^{n} (e_i e_j + f_i f_j) G_{ij} + (f_i e_j - e_i f_j) B_{ij} \tag{A.9}$$

$$Q_i = \sum_{j=1}^{n} (f_i e_j - e_i f_j) G_{ij} - (e_i e_j + f_i f_j) B_{ij} \tag{A.10}$$

The complex current flowing into the bus i is given by

$$\hat{a}_i + j\hat{b}_i = \sum_{j=1}^{n} (G_{ij} + j B_{ij}) (e_j + j f_j) \tag{A.11}$$

Then, the elements of the Jacobian $[J^r]$ defined in equation (2.11) are as given below :

For $i \neq j$

$$\frac{\partial P_i}{\partial e_j} = -\frac{\partial Q_i}{\partial f_j} = G_{ij} e_i + B_{ij} f_i \tag{A.12}$$

$$\frac{\partial P_i}{\partial f_j} = \frac{\partial Q_i}{\partial e_j} = -B_{ij} e_i + G_{ij} f_i \tag{A.13}$$

APPENDIX B

MATRIX MODIFICATION TECHNIQUES

B.1 INVERSION OF A MODIFIED MATRIX

Let the changes in the original matrix $[B_o]$ be represented as

$$[\Delta B] = \begin{array}{c c} & \begin{array}{cc} i & j \end{array} \\ \begin{array}{c} i \\ j \end{array} & \left[\begin{array}{c|c} b_{ii} & b_{ij} \\ \hline b_{ji} & b_{jj} \end{array}\right] \end{array} \tag{B.1}$$

If $b_{ii} = b_{ij} = b_{ji} = b_{jj} = b$, the new matrix $[B_1]$ can be expressed as

$$[B_1] = [B_o] + b\,[M]^T [M] \tag{B.2}$$

where $[M]$ is a highly sparse row vector given by

$$[0,0,0 \ldots \overset{i}{1},\ 0,0,0 \ldots \overset{j}{1},\ 0,0,0]$$

Then $$[B_1]^{-1} = \{[B_o] + b[M]^T [M]\}^{-1} \tag{B.3}$$

Using Sherman-Morrison formula [13] and expanding the equation (B.3), we get

$$\begin{aligned} [B_1]^{-1} &= [B_o]^{-1} - b(1+b[M][B_o]^{-1}[M]^T)^{-1}([B_o]^{-1}[M]^T[M][B_o]^{-1}) \\ &= [B_o]^{-1} - (\tfrac{1}{b} + [M][B_o]^{-1}[M]^T)^{-1}([B_o]^{-1}[M]^T[M][B_o]^{-1}) \end{aligned} \tag{B.4}$$

Let $[X] = [B_o]^{-1} [M]^T$ (B.5)

$$a = \left(\frac{1}{b} + [M][X]\right)^{-1} \qquad (B.6)$$

Using (B.5) and (B.6) in equation (B.4), we get

$$[B_1]^{-1} = [B_o]^{-1} - a[X][M][B_o]^{-1} \qquad (B.7)$$

Let the modified matrix equation be expressed as

$$[B_1][X_1] = [Z_1] \qquad (B.8)$$

i.e. the solution vector $[X_1] = [B_1]^{-1} [Z_1]$ (B.9)

Substituting the expression for $[B_1]^{-1}$ from (B.7) in (B.9), we obtain

$$[X_1] = [X_o] + [\Delta X] \qquad (B.10)$$

where $[X_o] = [B_o]^{-1} [Z_1]$ (B.11)

and $[\Delta X] = -a[X][M][X_o]$ (B.12)

Solution Procedure :

The solution vector $[X_1]$ can be calculated using the factors of the original matrix in the following manner.

Step 1 : Compute the vector $[X]$ and the scalar 'a' from equations (B.5) and (B.6)

Step 2 : Compute $[X_o]$ by a repeat solution using the factors of $[B_o]$ in equation (B.11)

Step 3 : Compute the correction vector $[\Delta X]$ from eqn. (B.12) and hence the solution vector $[X_1]$ from eqn. (B.10).

B.2 CALCULATION OF SENSITIVITY FACTOR

In Chapter II, the consideration of Q-limit violations on the voltage controlled buses using sensitivity factors in the method of FDLR and NRM load flow techniques has been discussed. Here, the calculation of these sensitivity factors following reference [29] is given.

Each P-V bus is checked for its Q-limits. If there is a violation, then the concerned bus is switched to a P-Q bus. That means, the matrix $[B'']$, in equation (2.29) is modified by an extra row and column as

$$[B'']_{new} = \left[\begin{array}{c|c} [B''] & C_1 \\ \hline C_1^T & C_2 \end{array}\right] \tag{B.13}$$

Let the order of the original matrix be (n-1) x (n-1). If the new P-Q bus is represented as n, then the order of $[B'']_{new}$ will be nxn. The factors of the symmetric matrix $[B'']$ are expressed as

$$[B''] = [U]^T \quad [D]^{-1} \; [U] \tag{B.14}$$

where $[U]$ is the upper triangular matrix with unit diagonal elements and $[D]^{-1}$ is the diagonal matrix. The factors of $[B'']_{new}$ can be obtained by adding the nth column to $[U]$ and a

diagonal element to $[D]$ in the existing factors. These additional factors can be obtained from the factors of the original matrix in the following manner.

Solution Procedure :

Step 1 : Obtain the intermediate vector $[F_1]$ by forward operation on $[C_1]$ and $[U]^T$.

Step 2 : Obtain the additional factors U_{1n}, U_{2n}, ... $U_{n-1,n}$ by multiplying $[D]$ and $[F_1]$ and $U_{nn} = 1$.

Step 3 : Obtain the nth element of $[D]$ from

$$D_{nn} = (C_2 - \sum_{j=1}^{n-1} U_{jn}^2/D_{jj})^{-1} \tag{B.15}$$

The element D_{nn} as obtained from (B.15) is known as the sensitivity factor S used for Q-limits.

The above procedure can be followed with slight modifications for use in equation (2.46). Here, the matrix $[J]$ is not symmetric. Hence, both the lower and upper triangular factors of the original matrix need to be stored and operated to obtain the additional column as well as row factors for the calculation of sensitivity factors.

B.3 MATRIX REDUCTION AND UPDATING TECHNIQUES

In Chapter II, NETR load flow solution using the network reduction technique has been proposed and in Chapter III, it has been extended for contingency evaluation using the matrix updating algorithm.

Here, we present the essential steps of the matrix reduction and updating techniques used in NETR load flow and contingency evaluation. The detailed derivation of these steps are given in reference [21]

B.3.1 Reduction process

Consider the matrix of order nxn given by

$$[Y_n] = \begin{array}{c|c} & \begin{array}{cc} m & n-m \end{array} \\ \begin{array}{c} m \\ n-m \end{array} & \left[\begin{array}{c|c} Y_A & Y_C \\ \hline Y_C^T & Y_D \end{array}\right] \end{array} \tag{B.16}$$

The matrix $[Y_n]$ is reduced to $[Y_m]$ of order mxm by applying Gaussian elimination on $[Y_n]$ and eliminating $[Y_C]$ and $[Y_C^T]$ by using an appropriate unit upper triangular matrix.

Let

$$[Y_n] = \begin{array}{c|c} & \begin{array}{cc} n-1 & 1 \end{array} \\ \begin{array}{c} n-1 \\ 1 \end{array} & \left[\begin{array}{c|c} Y_{an} & Y_{cn} \\ \hline Y_{cn}^T & Y_{nn} \end{array}\right] \end{array} \tag{B.17}$$

and

$$[U_n] = \begin{bmatrix} 1 & & & & \hat{u}_n \\ & 1 & & & \\ & & 1 & & \\ & & & \cdot & \\ & & & & 1 \end{bmatrix} \qquad \hat{u}_n = -\frac{Y_{cn}}{Y_{nn}} \tag{B.18}$$

Then

$$[\,U_n\ Y_n\ U_n^T\,] = \left[\begin{array}{c|c} Y_{n-1} & 0 \\ \hline 0 & Y_{nn} \end{array}\right] \tag{B.19}$$

where $Y_{n-1} = Y_{an} - \dfrac{Y_{cn}\ Y_{cn}^T}{Y_{nn}}$

i.e. nth column and row of $[Y_n]$ are eliminated.

Continuing the above procedure, we get

$$[\,U\ Y_n\ U^T\,] = \left[\begin{array}{c|c} Y_m & 0 \\ \hline 0 & D \end{array}\right] \tag{B.20}$$

where

$$[\,U\,] = [\,U_{m+1},\ U_{m+2}\ \cdots\ U_n\,]$$

$$[\,D\,] = \begin{bmatrix} d_{m+1} & & & 0 \\ & \ddots & & \\ & & d_{n-1} & \\ 0 & & & d_n \end{bmatrix} \tag{B.21}$$

The values of U_{m+1}, U_{m+2}, ... U_n and d_{m+1}, d_{m+2}, ..., d_n, obtained by Gaussian elimination procedure are stored for updating the matrix $[Y_m]$ for a given change in $[Y_n]$.

B.3.2 Matrix updating algorithm

Let the change in matrix $[Y_n]$ be given as

$$[\Delta Y_n] = [\hat{C}^n] = \begin{array}{cc} & \begin{array}{cc} i & j \end{array} \\ \begin{array}{c} i \\ j \end{array} & \left[\begin{array}{c|c} \Delta Y_{ii} & \Delta Y_{ij} \\ \hline \Delta Y_{ji} & \Delta Y_{jj} \end{array}\right] \end{array} = [\hat{C}^n]^T \quad (2x2) \tag{B.22}$$

Let

$[X^n]$ be a highly sparse matrix of order nx2

$$= \left[\begin{array}{cc} 0 & 0 \\ 0 & 0 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{array}\right] \begin{array}{l} \\ \\ \\ \text{ith row} \\ \\ \text{jth row} \\ (nx2) \end{array} = \left[\begin{array}{c} X_t^n \\ \hline X_n^n \end{array}\right] \begin{array}{l} (n-1)x2 \\ \\ (1x2) \end{array} \tag{B.23}$$

and $[h_o]$ be a 2x1 vector to be used as a temporary storage.

The main steps of the algorithm are as follows :

1. If $i < j < n$, then set $k = j$; otherwise set $k = n$
2. $[h_o^k]^T = [X_k^k]\ [\hat{C}^k]$
3. $D_k = d_k + [X_k^k]\ [h_o^k]$
4. $[X^{k-1}] = [X_t^k] + [\hat{u}_k]\ [X_k^k]$

5. $[U_k] = [\hat{u}_k] - [X^{k-1}]\,[h_o^k]/D_k$

6. $[\hat{C}^{k-1}] = [\hat{C}^k] - [h_o^k][h_o^k]^T/D_k$

$$k = k - 1$$

If k > m, go to Step (2); otherwise, go to step (7).

7. Obtain the change $[\Delta Y_m] = [X^m\,\hat{C}^m\,X^{m^T}]$ and add the change to $[Y_m]$.

APPENDIX C

CONVERGENCE THEOREM

The convergence theorem used in Chapter VI is as follows :

Let $\hat{F}$ be continuously differentiable and $[A(x)]$ be non-singular matrix with elements continuous in the ball

$$\mathcal{R} = \{ x \in IR^N \mid \|x - x^0\| < \hat{\varepsilon} \}$$

Let us define

$$\text{Contraction constant} = C_c = \max_{\xi \in \mathcal{R}} \| D\phi(\xi) \|$$

Suppose

i) $C_c < 1$

ii) $\|\phi(x^0) - x^0\| < (1 - C_c)\hat{\varepsilon}$

Then,

1) there exists a unique solution of $\hat{F}(x) = Z$ in $\mathcal{R}$

2) the sequence $\{x^0, x^1, \ldots\}$ generated by ϕ will converge to the fixed point x^s of ϕ in $\mathcal{R}$

3) $\|x^k - x^s\| < \dfrac{C_c}{1 - C_c} \|x^k - x^{k-1}\|$

where IR^N = N-dimensional vector space.

$\|x\| = \max_i \{|x_i|\}$ i.e., ∞-norm on IR^N is used.

$\|A\| = \max_i \{\sum_j |a_{ij}|\}$

and $D\phi(\xi)$ denotes the derivative of ϕ at ξ

APPENDIX D

DATA FOR TEST SYSTEMS

In this appendix, the data for IEEE 14 bus, 30 bus and 57 bus test systems and for a heavily loaded 28 bus system [38] are given. Base MVA = 100. The data is compiled in the following manner :

1) Bus data
2) Line data
3) Transformer data
4) Shunt capacitor data
5) Voltage controlled or P-V bus data
6) Generator data for optimal load flow problem

D.1 IEEE 14 BUS TEST SYSTEM

D 1.1 Bus data

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
1	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	94.2	19.0
4	0.0	0.0	47.8	-3.9
5	0.0	0.0	7.6	1.6
6	0.0	0.0	11.2	7.5

continued..

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	29.5	16.6
10	0.0	0.0	9.0	5.8
11	0.0	0.0	3.5	1.8
12	0.0	0.0	6.1	1.6
13	0.0	0.0	13.5	5.8
14	0.0	0.0	14.9	5.0

D 1.2 Line data

Line No.	Buses		Line impedance		Half line charging susceptance p.u.
	From	To	R in p.u.	X in p.u.	
1	1	2	0.01938	0.05917	0.02640
2	2	3	0.04699	0.19797	0.02190
3	2	4	0.05811	0.17632	0.01870
4	1	5	0.05403	0.22304	0.02460
5	2	5	0.05695	0.17388	0.01700
6	3	4	0.06701	0.17103	0.01730
7	4	5	0.01335	0.04211	0.00640

continued ..

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
8	5	6	0.0	0.25202	0.0
9	4	7	0.0	0.20912	0.0
10	7	8	0.0	0.17615	0.0
11	4	9	0.0	0.55618	0.0
12	7	9	0.0	0.11001	0.0
13	9	10	0.03181	0.08450	0.0
14	6	11	0.09498	0.19890	0.0
15	6	12	0.12191	0.25581	0.0
16	6	13	0.06615	0.13027	0.0
17	9	14	0.12711	0.27038	0.0
18	10	11	0.08205	0.19207	0.0
19	12	13	0.22092	0.19988	0.0
20	13	14	0.17093	0.34802	0.0

D 1.3 Transformer data

Transformer No.	Buses From	Buses To	Tap setting
1	4	7	0.978
2	4	9	0.969
3	5	6	0.932

D 1.4 Shunt capacitor data

Bus No.	Susceptance p.u.
9	0.190

D 1.5 Voltage controlled bus data (P-V buses)

Bus No.	Voltage magnitude p.u.	Reactive power limits Minimum MVAR	Reactive power limits Maximum MVAR
2	1.045	-40.0	50.0
3	1.010	0.0	40.0
6	1.070	-6.0	24.0
8	1.090	-6.0	24.0

Slack bus voltage = $1.06\angle 0$

D 1.6 Generator data

Bus No.	P_G^{min} MW	P_G^{max} MW	Q_G^{min} MVAR	Q_G^{max} MVAR	Cost coefficients a_{oi}	b_{oi}	c_{oi}
1	50.0	200.0	-20.0	100.0	105.0	2.45	0.005
2	20.0	100.0	-40.0	50.0	44.4	3.51	0.005
3			-40.0	60.0			
6	20.0	100.0	- 6.0	45.0	40.6	3.89	0.005
8			- 6.0	45.0			

continued ..

Lower limits on voltage magnitude at all the buses including the slack bus 1 = 0.90 p.u.

Upper limits on voltage magnitude at all the buses excepting the slack bus = 1.1 p.u.; for slack bus = 1.06 p.u.

Cost of generation $F_i = (a_{oi} + b_{oi} P_{Gi} + c_{oi} P_{Gi}^2)$ \$ per hr.

D.2 IEEE 30 BUS TEST SYSTEM

D 2.1 Bus data

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
1	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	2.4	1.2
4	0.0	0.0	7.6	1.6
5	0.0	0.0	94.2	19.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	22.8	10.9
8	0.0	0.0	30.0	30.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	5.8	2.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	11.2	7.5
13	0.0	0.0	0.0	0.0

continued ..

Lower limits on voltage magnitude at all the buses including the slack bus 1 = 0.90 p.u.

Upper limits on voltage magnitude at all the buses excepting the slack bus = 1.1 p.u.; for slack bus = 1.06 p.u.

Cost of generation $F_i = (a_{oi} + b_{oi} P_{Gi} + c_{oi} P_{Gi}^2)$ \$ per hr.

D.2 IEEE 30 BUS TEST SYSTEM

D 2.1 Bus data

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
1	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	2.4	1.2
4	0.0	0.0	7.6	1.6
5	0.0	0.0	94.2	19.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	22.8	10.9
8	0.0	0.0	30.0	30.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	5.8	2.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	11.2	7.5
13	0.0	0.0	0.0	0.0

continued ..

Bus No.	Generation MW	Generation MVAR	Load MW	Load MVAR
14	0.0	0.0	6.2	1.6
15	0.0	0.0	8.2	2.5
16	0.0	0.0	3.5	1.8
17	0.0	0.0	9.0	5.8
18	0.0	0.0	3.2	0.9
19	0.0	0.0	9.5	3.4
20	0.0	0.0	2.2	0.7
21	0.0	0.0	17.5	11.2
22	0.0	0.0	0.0	0.0
23	0.0	0.0	3.2	1.6
24	0.0	0.0	8.7	6.7
25	0.0	0.0	0.0	0.0
26	0.0	0.0	3.5	2.3
27	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0
29	0.0	0.0	2.4	0.9
30	0.0	0.0	10.6	1.9

D 2.2 Line data

Line No.	Buses From	To	Line impedance R in p.u.	X in p.u.	Half line charging susceptance p.u.
1	1	2	0.0192	0.0575	0.0132
2	1	3	0.0452	0.1852	0.0102
3	2	4	0.0570	0.1737	0.0092
4	3	4	0.0132	0.0379	0.0021
5	2	5	0.0472	0.1083	0.0104
6	2	6	0.0581	0.1763	0.0093
7	4	6	0.0119	0.0414	0.0023
8	5	7	0.0460	0.1160	0.0051
9	6	7	0.0267	0.0820	0.0042
10	6	8	0.0120	0.0420	0.0022
11	6	9	0.0	0.2080	0.0
12	6	10	0.0	0.5560	0.0
13	9	11	0.0	0.2080	0.0
14	9	10	0.0	0.1100	0.0
15	4	12	0.0	0.2560	0.0
16	12	13	0.0	0.1400	0.0
17	12	14	0.1231	0.2559	0.0
18	12	15	0.0662	0.1304	0.0
19	12	16	0.0945	0.1987	0.0
20	14	15	0.2210	0.1997	0.0
21	16	17	0.0824	0.1932	0.0

continued ..

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
22	15	18	0.1070	0.2185	0.0
23	18	19	0.0639	0.1292	0.0
24	19	20	0.0340	0.0680	0.0
25	10	20	0.0936	0.2090	0.0
26	10	17	0.0324	0.0845	0.0
27	10	21	0.0348	0.0749	0.0
28	10	22	0.0727	0.1499	0.0
29	21	22	0.0116	0.0236	0.0
30	15	23	0.1000	0.2020	0.0
31	22	24	0.1150	0.1790	0.0
32	23	24	0.1320	0.2700	0.0
33	24	25	0.1885	0.3292	0.0
34	25	26	0.2544	0.3800	0.0
35	25	27	0.1093	0.2087	0.0
36	28	27	0.0	0.3960	0.0
37	27	29	0.2198	0.4153	0.0
38	27	30	0.3202	0.6027	0.0
39	29	30	0.2399	0.4533	0.0
40	8	28	0.0636	0.2000	0.0107
41	6	28	0.0169	0.0599	0.0032

D 2.3 Transformer data

Transformer No.	Buses From	Buses To	Tap setting
1	6	9	0.978
2	6	10	0.969
3	4	12	0.932
4	28	27	0.968

D 2.4 Shunt capacitor data

Bus No.	Susceptance p.u.
10	0.19
24	0.04

D 2.5 Voltage controlled bus data

Bus No.	Voltage magnitude p.u.	Reactive power limits Minimum MVAR	Reactive power limits Maximum MVAR
2	1.045	-20.0	60.0
5	1.010	-15.0	62.5
8	1.010	-15.0	50.0
11	1.050	-10.0	40.0
13	1.050	-15.0	45.0

Slack bus voltage = $1.05\underline{/0}$

D 2.6 Generator data

Bus No.	P_G^{min} MW	P_G^{max} MW	Q_G^{min} MVAR	Q_G^{max} MVAR	Cost coefficients a_{oi}	b_{oi}	c_{oi}
1	50.0	200.0	-20.0	250.0	0.0	2.00	0.00375
2	20.0	80.0	-20.0	100.0	0.0	1.75	0.01750
5	15.0	50.0	-15.0	80.0	0.0	1.00	0.06250
8	10.0	35.0	-15.0	60.0	0.0	3.25	0.00834
11	10.0	30.0	-10.0	50.0	0.0	3.00	0.0250
13	12.0	40.0	-15.0	60.0	0.0	3.00	0.0250

Lower limits on voltage magnitude at all the buses including the slack bus 1 = 0.95 p.u.

Upper limits on voltage magnitude at all the generator buses excluding the slack bus = 1.1 p.u.

Upper limits on voltage magnitude at all the load buses and slack bus = 1.05 p.u.

Cost of generation $F_i = (a_{oi} + b_{oi} P_{Gi} + c_{oi} P_{Gi}^2)$ £ per hr.

D.3 IEEE 57 BUS TEST SYSTEM

D 3.1 Bus data

Bus No.	Generation MW	Generation MVAR	Load MW	Load MVAR
1	0.0	0.0	55.0	17.0
2	0.0	0.0	3.0	88.0

continued ..

Bus No.	Generation MW	Generation MVAR	Load MW	Load MVAR
3	40.0	0.0	41.0	21.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	13.0	4.0
6	0.0	0.0	75.0	2.0
7	0.0	0.0	0.0	0.0
8	450.0	0.0	150.0	22.0
9	0.0	0.0	121.0	26.0
10	0.0	0.0	5.0	2.0
11	0.0	0.0	0.0	0.0
12	310.0	0.0	377.0	24.0
13	0.0	0.0	18.0	2.3
14	0.0	0.0	10.5	5.3
15	0.0	0.0	22.0	5.0
16	0.0	0.0	43.0	3.0
17	0.0	0.0	42.0	8.0
18	0.0	0.0	27.2	9.8
19	0.0	0.0	3.3	0.6
20	0.0	0.0	2.3	1.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	6.3	2.1
24	0.0	0.0	0.0	0.0

continued ..

Bus No.	Generation MW	Generation MVAR	Load MW	Load MVAR
25	0.0	0.0	6.3	3.2
26	0.0	0.0	0.0	0.0
27	0.0	0.0	9.3	0.5
28	0.0	0.0	4.6	2.3
29	0.0	0.0	17.0	2.6
30	0.0	0.0	3.6	1.8
31	0.0	0.0	5.8	2.9
32	0.0	0.0	1.6	0.8
33	0.0	0.0	3.8	1.9
34	0.0	0.0	0.0	0.0
35	0.0	0.0	6.0	3.0
36	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0
38	0.0	0.0	14.0	7.0
39	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0
41	0.0	0.0	6.3	3.0
42	0.0	0.0	7.1	4.4
43	0.0	0.0	2.0	1.0
44	0.0	0.0	12.0	1.8
45	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0

continued ..

Bus No.	Generation MW	Generation MVAR	Load MW	Load MVAR
47	0.0	0.0	29.7	11.6
48	0.0	0.0	0.0	0.0
49	0.0	0.0	18.0	8.5
50	0.0	0.0	21.0	10.5
51	0.0	0.0	18.0	5.3
52	0.0	0.0	4.9	2.2
53	0.0	0.0	20.0	10.0
54	0.0	0.0	4.1	1.4
55	0.0	0.0	6.8	3.4
56	0.0	0.0	7.8	2.2
57	0.0	0.0	6.7	2.0

D 3.2 Line data

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
1	1	2	0.0083	0.0280	0.0645
2	2	3	0.0298	0.0850	0.0409
3	3	4	0.0112	0.0366	0.0190
4	4	5	0.0625	0.1320	0.0129
5	4	6	0.0430	0.1480	0.0174
6	6	7	0.0200	0.1020	0.0138

continued ...

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
7	6	8	0.0339	0.1730	0.0235
8	8	9	0.0099	0.0505	0.0274
9	9	10	0.0369	0.1679	0.0220
10	9	11	0.0258	0.0848	0.0109
11	9	12	0.0648	0.2950	0.0386
12	9	13	0.0481	0.1580	0.0203
13	13	14	0.0132	0.0434	0.0055
14	13	15	0.0269	0.0869	0.0115
15	1	15	0.0178	0.0910	0.0494
16	1	16	0.0454	0.206	0.0273
17	1	17	0.0238	0.108	0.0143
18	3	15	0.0162	0.053	0.0272
19	4	18	0.0	0.555	0.0
20	4	18	0.0	0.43	0.0
21	5	6	0.0302	0.0641	0.0062
22	7	8	0.0139	0.0712	0.0097
23	10	12	0.0277	0.1262	0.0164
24	11	13	0.0223	0.0732	0.0094
25	12	13	0.0178	0.0580	0.0302
26	12	16	0.0180	0.0813	0.0108
27	12	17	0.0397	0.1790	0.0238

continued ...

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
28	14	15	0.0171	0.0547	0.0074
29	18	19	0.461	0.685	0.0
30	19	20	0.283	0.434	0.0
31	20	21	0.0	0.7767	0.0
32	21	22	0.0736	0.1170	0.0
33	22	23	0.0099	0.0152	0.0
34	23	24	0.1660	0.256	0.0042
35	24	25	0.0	1.182	0.0
36	24	25	0.0	1.230	0.0
37	24	26	0.0	0.0473	0.0
38	26	27	0.165	0.254	0.0
39	27	28	0.0618	0.0954	0.0
40	28	29	0.0418	0.0587	0.0
41	7	29	0.0	0.0648	0.0
42	25	30	0.135	0.2020	0.0
43	30	31	0.326	0.4970	0.0
44	31	32	0.507	0.7550	0.0
45	32	33	0.0392	0.0360	0.0
46	32	34	0.0	0.9530	0.0
47	34	35	0.052	0.0780	0.0016
48	35	36	0.043	0.0537	0.0008

continued ..

Line No.	Buses From	To	Line impedance R in p.u.	X in p.u.	Half line charging susceptance p.u.
49	36	37	0.029	0.0366	0.0
50	37	38	0.0651	0.1009	0.0010
51	37	39	0.0239	0.0379	0.0
52	36	40	0.0300	0.0466	0.0
53	22	38	0.0192	0.0295	0.0
54	11	41	0.0	0.7490	0.0
55	41	42	0.2070	0.3520	0.0
56	41	43	0.0	0.4120	0.0
57	38	44	0.0289	0.0585	0.0010
58	15	45	0.0	0.1042	0.0
59	14	46	0.0	0.0735	0.0
60	46	47	0.0230	0.0680	0.0016
61	47	48	0.0182	0.0233	0.0
62	48	49	0.0834	0.1290	0.0024
63	49	50	0.0801	0.1280	0.0
64	50	51	0.1386	0.2200	0.0
65	10	51	0.0	0.0712	0.0
66	13	49	0.0	0.1910	0.0
67	29	52	0.1442	0.1870	0.0
68	52	53	0.0762	0.0984	0.0
69	53	54	0.1878	0.2320	0.0

continued ..

Line No.	Buses From	To	Line impedance R in p.u.	X in p.u.	Half line charging susceptance p.u.
70	54	55	0.1732	0.2265	0.0
71	11	43	0.0	0.1530	0.0
72	44	45	0.0624	0.1242	0.0020
73	40	56	0.0	1.1950	0.0
74	56	41	0.553	0.5490	0.0
75	56	42	0.2125	0.3540	0.0
76	39	57	0.0	1.3550	0.0
77	57	56	0.1740	0.2600	0.0
78	38	49	0.1150	0.1770	0.003
79	38	48	0.0312	0.0482	0.0
80	9	55	0.0	0.1205	0.0

D 3.3 Transformer data

Transformer No.	Buses From	To	Tap setting
1	4	18	0.970
2	4	18	0.978
3	7	29	0.967
4	9	55	0.940
5	10	51	0.930

continued ..

Transformer No.	Buses From	To	Tap setting
6	11	41	0.955
7	11	43	0.958
8	13	49	0.895
9	14	46	0.900
10	15	45	0.955
11	21	20	1.043
12	24	25	1.000
13	24	25	1.000
14	24	26	1.043
15	34	32	0.975
16	39	57	0.980
17	40	56	0.958

D 3.4 Shunt capacitor data

Bus No.	Susceptance p.u.
18	0.100
25	0.059
53	0.063

D 3.5 Voltage controlled bus data (P.V. buses)

Bus No.	Voltage magnitude p.u.	Reactive power limits Minimum MVAR	Maximum MVAR
2	1.010	-17.0	50.0
3	0.985	-10.0	60.0
6	0.980	- 8.0	25.0
8	1.005	-140.0	200.0
9	0.980	- 3.0	9.0
12	1.015	-50.0	155.0

Slack bus voltage = $1.04\underline{/0}$

D 3.6 Generator data

Bus No.	P_G^{min} MW	P_G^{max} MW	Q_G^{min} MVAR	Q_G^{max} MVAR	Cost coefficients a_{oi}	b_{oi}	c_{oi}
1	100.00	500.00	-50.00	200.00	0.0	2.00	0.00375
2	100.00	400.00	-50.00	100.00	0.0	1.75	0.0175
3	50.00	300.00	-50.00	60.00	0.0	1.00	0.0225
6	50.00	300.00	-40.00	65.00	0.0	1.00	0.0250
8	50.00	300.00	-30.00	100.00	0.0	3.25	0.0085
9	50.00	300.00	-20.00	50.00	0.0	2.00	0.0042
12	50.00	300.00	-50.00	200.00	0.0	3.00	0.0250

continued ...

Lower limits on voltage magnitude at all the buses including the slack bus = 0.90 p.u.

Upper limits on voltage magnitude at all the buses excepting the slack bus = 1.1 p.u.; for slack bus = 1.05 p.u.

Cost of generation $F_i = (a_{oi} + b_{oi} P_{Gi} + c_{oi} P_{Gi}^2)$ £ per hr.

D.4 28 BUS HEAVILY LOADED SYSTEM

D 4.1 Bus data

Bus No.	Voltage magnitude p.u.	Generation MW	Generation MVAR	Load MW	Load MVAR
1	1.05	0.0	0.0	0.0	0.0
2	1.05	152.0	0.0	0.0	0.0
3	1.05	390.0	0.0	0.0	0.0
4	1.05	49,0	0.0	0.0	0.0
5	1.05	440.0	0.0	0.0	0.0
6	1.05	191.0	0.0	0.0	0.0
7	1.00	0.0	0.0	145.0	50.0
8	1.00	0.0	0.0	265.0	-22.0
9	1.00	0.0	0.0	381.0	26.0
10	1.00	0.0	0.0	384.0	-2.0
11	1.00	0.0	0.0	374.0	34.0
12	1.00	0.0	0.0	129.0	3.0
13	1.0	0.0	0.0	135,0	58.0

continued ..

Bus No.	Voltage magnitude p.u.	Generation MW	Generation MVAR	Load MW	Load MVAR
14	1.00	0.0	0.0	60.8	7.0
15	1.00	0.0	0.0	118.0	-18.0
16	1.00	0.0	0.0	75.0	44.0
17	1.00	0.0	0.0	139.0	52.0
18	1.00	0.0	0.0	0.0	0.0
19	1.00	0.0	0.0	0.0	0.0
20	1.00	0.0	0.0	0.0	0.0
21	1.00	0.0	0.0	0.0	0.0
22	1.00	0.0	0.0	0.0	0.0
23	1.00	0.0	0.0	0.0	0.0
24	1.00	0.0	0.0	0.0	0.0
25	1.00	0.0	0.0	0.0	0.0
26	1.00	0.0	0.0	0.0	0.0
27	1.00	0.0	0.0	0.0	0.0
28	1.00	0.0	0.0	0.0	0.0

D 4.2 Line data

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
1	7	28	0.0140	0.070	0.0
2	8	27	0.0078	0.039	0.0

continued ..

Line No.	Buses From	To	Line impedance R in p.u.	X in p.u.	Half line charging susceptance p.u.
3	9	26	0.0058	0.029	0.0
4	10	25	0.0054	0.027	0.0
5	11	12	0.0070	0.035	0.0
6	12	22	0.0062	0.031	0.0
7	12	23	0.0010	0.005	0.0
8	13	23	0.0196	0.098	0.0
9	14	24	0.0280	0.140	0.0
10	15	21	0.0118	0.059	0.0
11	16	21	0.0294	0.147	0.0
12	17	18	0.0280	0.140	0.0
13	17	4	0.0258	0.129	0.0
14	18	20	0.0220	0.110	0.0
15	18	22	0.0062	0.031	0.0
16	19	20	0.0060	0.030	0.0
17	19	27	0.0296	0.148	0.0
18	19	28	0.0242	0.121	0.0
19	19	3	0.0070	0.035	0.0
20	19	1	0.0200	0.100	0.0
21	20	21	0.0068	0.034	0.0
22	20	26	0.0038	0.019	0.0
23	20	2	0.0112	0.056	0.0

continued ...

Line No.	Buses From	Buses To	Line impedance R in p.u.	Line impedance X in p.u.	Half line charging susceptance p.u.
24	21	22	0.0220	0.110	0.0
25	22	23	0.0054	0.027	0.0
26	22	6	0.0070	0.035	0.0
27	22	1	0.0054	0.027	0.0
28	23	24	0.0072	0.036	0.0
29	24	5	0.0104	0.052	0.0
30	25	26	0.0038	0.019	0.0
31	26	27	0.0076	0.038	0.0
32	26	28	0.0128	0.064	0.0

D 4.3 Shunt capacitor data

Bus No.	Susceptance p.u.
7	1.2069
8	1.0252
9	2.0804
10	1.6665
11	1.5422
13	1.0042
14	0.2080
15	0.4476
16	0.7768
17	0.5868

CURRICULUM VITAE

1. Candidate's Name : N. ARUMUGAM

2. Academic Background :

Degree	Specialization	University	Year
B.E.(Hons)	Electrical Engg.	Annamalai University (Tamil Nadu)	1962
M.E.	Power Systems (High Voltage Engg.)	Indian Institute of Science (Bangalore)	1964

3. Publications :

(i) "A fast algorithm for on-line load flow and contingency evaluation" (with M.A. Pai and R.P. Aggarwal), IFAC International Symposium on "Computer Applications in Large Scale Power Systems, New Delhi, Vol. I (Book), pp. 132-138, August, 1979.

(ii) "Load flow solution by Newton-Richardson method and its adaptation to optimal load dispatch" (with R.P.Aggarwal and M.A. Pai) - Paper published in the Journal of Electrical Power and Energy Systems, England, Vol.2, No.3, pp. 129-132, July 1980.

(iii) "Load flow and optimal load flow analysis of large scale power systems by a two level computation" (with R.P. Aggarwal and M.A. Pai), Proceedings of the Third International Symposium on Large Engineering Systems held at the Memorial University of Newfoundland St. John's, Newfoundland, Canada, pp. 293-299, July 1980.

(iv) "A comparative study of contingency evaluation methods for on-line power system security" (with M.A. Pai and R.P. Aggarwal), Diamond Jubilee Symposium on 'Optimization of Electrical Power Apparatus and Systems', Banaras Hindu University, India, (Book), pp.94-99, March 1979.

(v) "Role and impact of computers on power systems" - Paper presented at the 'National Seminar on Computer Applications in Science, Engineering and Business Administration', Annamalai University, India, July 1979.